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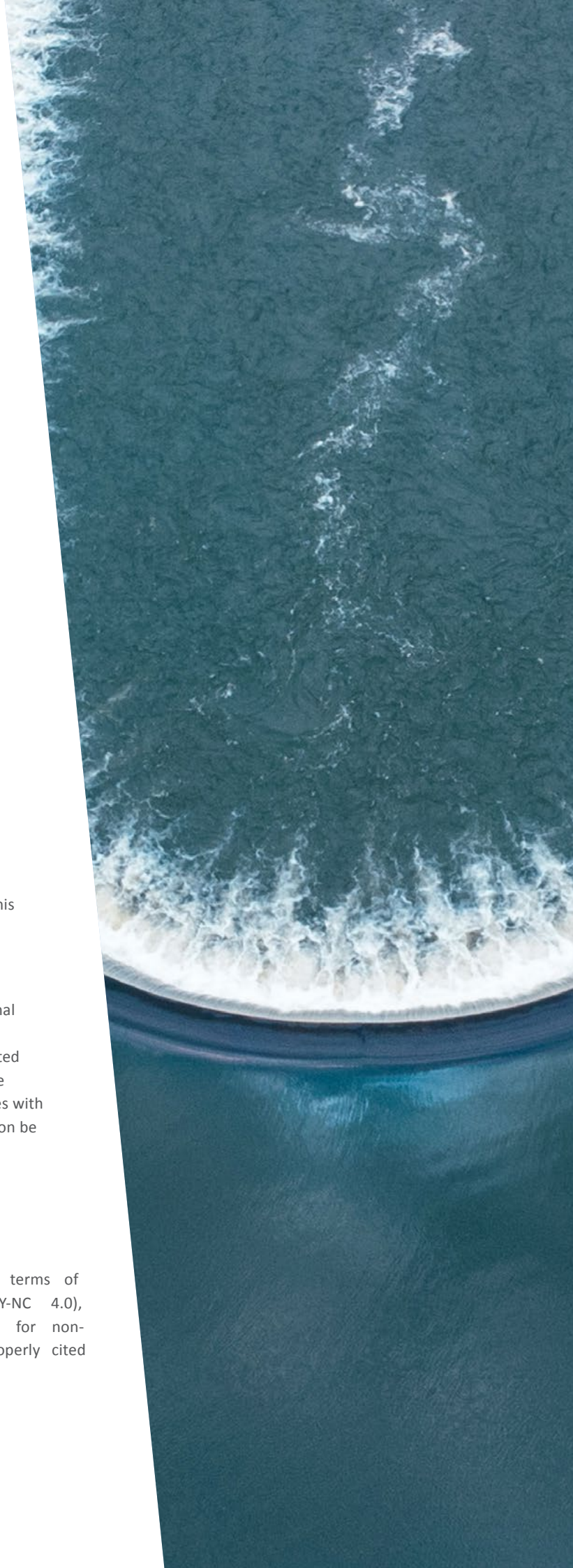


Global Trends & Challenges

in Water Science, Research and Management

A compendium of hot topics and features from IWA Specialist Groups

FOURTH EDITION



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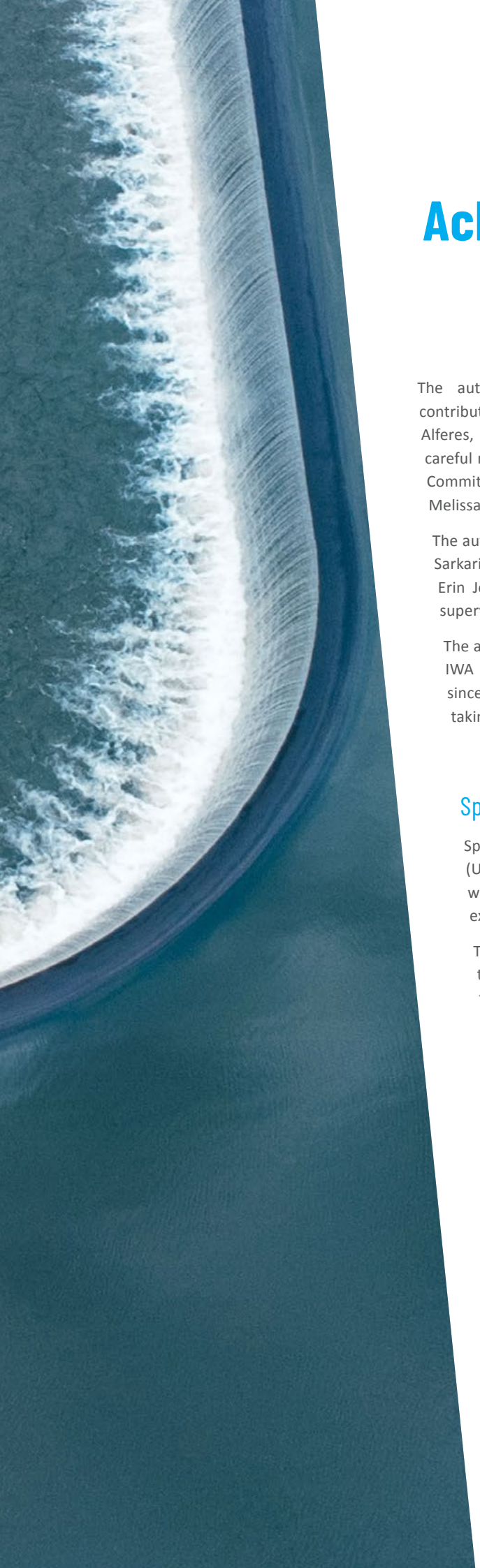
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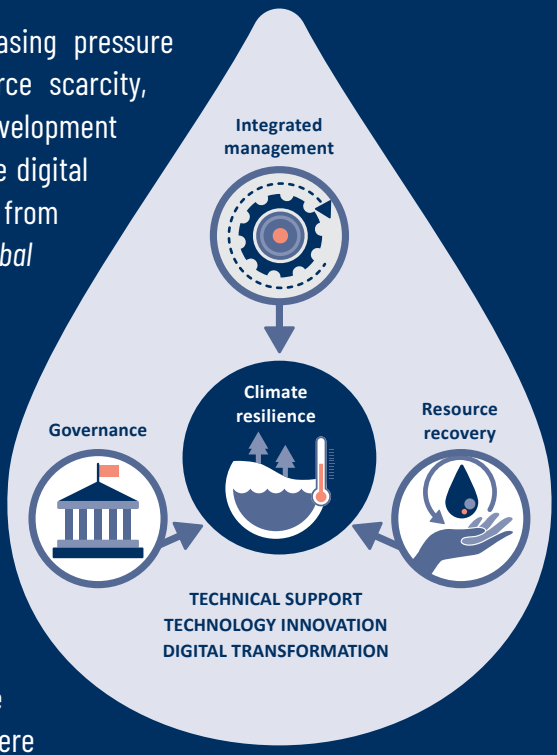
Their dedication, knowledge, and collaborative efforts were essential to the development and quality of this work. We sincerely appreciate the time, commitment, and contributions of everyone who helped shape and strengthen this report.



Preface

Since its inaugural edition, the *IWA Global Trends Report* has provided a biennial platform for the collective expertise of IWA Specialist Groups and Clusters, showcasing the emerging ideas, scientific advances and practical innovations shaping the global water agenda. This fourth edition continues that mission at a time when the urgency has never been greater. Despite continuous efforts made globally in past decades, billions of people still lack access to safe drinking water, and surface water bodies continue to be affected by the disposal of untreated or minimally treated wastewater. This lack of basic services has dire implications, and the consequences extend far beyond environmental degradation, and include undermining public health, constraining economic development, affecting quality of life and creating disparities in equity.

In the meantime, water systems worldwide are under increasing pressure from climate change, population growth, urbanisation, resource scarcity, pollution and rising societal expectations. In parallel, rapid development in artificial intelligence has also been remarkably influencing the digital transformation of the water sector. The collective contributions from academia to practitioners found throughout this edition of the *Global Trends Report* make one point clear:



The challenge is no longer incremental improvement, but the transformation of water systems to become resilient, adaptive, equitable and sustainable in the face of unprecedented global change.

As we present this edition to the international water community, we do so with both urgency and optimism: urgency, because the pressures on water systems are intensifying; optimism, because the knowledge, innovation and collaboration showcased here demonstrate that the sector is well equipped and committed to shape a more secure water future.

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Introduction

Each edition of the IWA Global Trends Report focuses on current topics that are driving research and innovation in the global water agenda. This 2026 edition has identified five interconnected themes that are defining the future of water management worldwide.

- Climate resilience and water security
- Digital water and innovation
- Water, sanitation and public health
- Circular economy and sustainable water management
- Water governance, finance and equity.

Within the themes, you will find topical contributions from the 36 IWA's Specialist Groups and Cluster providing insights into emerging challenges, technological developments and practical experience from diverse institutional and geographical contexts. Although organised according to five themes, many contributions span multiple areas, reflecting the interdependence of resilience, innovation, public health, circularity, governance, finance and equity.

As populations rise, creating more demand, and changes in climate and weather patterns further impact the world's water resources and supplies, integrated and circular resource management will be critical to ensuring water security and resilience. The transformation of what was once thought of as waste into valuable resources – water, nutrients, energy – is no longer an afterthought and thankfully, becoming part of mainstream water sector thinking.

The advancement of digital technologies presents the water industry with tools to help model systems, monitor quantity and quality, predict risk and train the next generation of water workers. But to truly impact water security and climate resilience, technologies must be integrated into the governance structure, addressing staff capacity and defining how information gleaned will be used in decision making.

How these themes coalesce to bring bold ideas and solutions is core to the role of IWA's Specialist Groups towards the IWA Mission Despite one's individual area of practice, our community remains centred in connecting disciplines, sharing knowledge and translating innovation into practice. This Compendium reflects that collective effort, bringing together diverse perspectives from across the global water community, united by a shared commitment to addressing the sector's most pressing challenges.

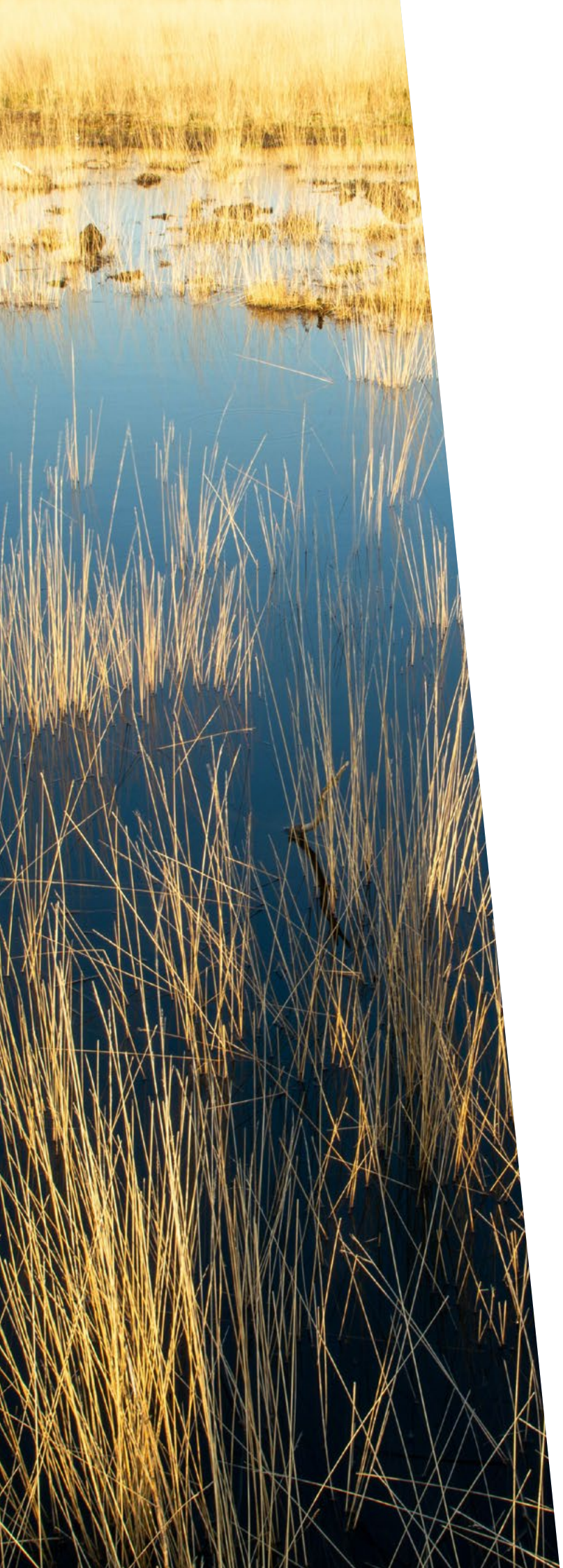


List of abbreviations

3T	Tariffs, taxes, and transfers model
ADS	Amplicon deep sequencing
AGS	Aerobic granular sludge
AI	Artificial intelligence
AMR	Antimicrobial resistance
AOCF	Advanced oxidation, coagulation, and filtration
AOPs	Advanced oxidation processes
AR	Augmented reality
ARB	Antibiotic-resistant bacteria/Anode-respiring bacteria
ARG	Antibiotic resistance genes
AS	Activated sludge
AUV	Autonomous underwater vehicle
BAFs	Biological aerated filters
BNR	Biological nutrient removal
CAPEX	Capital expenditures
CFD	Computational fluid dynamics
CI/CD	Continuous integration and continuous delivery/deployment
COD	Chemical oxygen demand,
CSO	Combined sewer overflow
CSTRs	Continuous stirred-tank reactors
CVP	Central Valley Project
DaaS	Data as a Service
DBPs	Disinfection by-products
ddPCR	Droplet digital PCR
DDPG	Deep deterministic policy gradient
DFOS	Distributed fibre optic sensing
DMA	District metered area
DMF	Direct membrane filtration
DMR	Discharge monitoring reports
DO	Dissolved oxygen
dPCR	Digital PCR
DPR	Direct potable reuse
DSG	Disinfection specialist group's
DT	Digital twin
DTW	Deep tubewells
DWTP	Drinking water treatment plant
EAOPs	Electrochemical advanced oxidation processes
EBPR	Enhanced biological P removal
ESG criteria	environmental, social, and governance
EWA	European water council
EWS	Early warning system
FIB	Faecal indicator bacteria
FISH	Fluorescence in situ hybridisation
FS	Faecal sludge
FSTP	Faecal Sludge Treatment Plant
FSTP,	faecal sludge treatment plant
FWS	Free water surface
GFPD	Genetic faecal pollution diagnostics
GHG	Greenhouse gas
GIS	Geographic information systems
GMPs	Good modelling practices
GPT	Generative pre-trained transformers
HAA	Haloacetic acids
HATS	Hong Kong Harbour Area Treatment Scheme
HDPE	High-density polyethylene
HF	Horizontal flow
HF-TW	Horizontal-flow treatment wetland
HRSD	The Hampton Roads Sanitation District
ICA	Instrumentation, control and automation
IDA	Intermediate deep aquifers

IDTW	Intermediate-depth well
IE	Ion exchange
IFAS	Integrated fixed-film active sludge
IHP	Intergovernmental hydrological programme
IoD	Internet of drones
IoT	Internet of Things
IPR	Indirect potable reuse
IQR method	Interquartile range
IRHA	International Rainwater Harvesting Alliance
IT	Information technology
IUWM	Integrated Urban Water Management
JCUD	Joint Committee on Urban Drainage
JECFA	Joint FAO/WHO Expert Committee on Food Additives
LAC	Latin America and the Caribbean
LEEFT	Locally enhanced electric field treatment,
LIMS	Laboratory information management system
LLM	Large language model
MABR	Membrane-aerated biofilm reactor
MAR	Managed aquifer recharge
MBBR	Moving bed biofilm reactor
MBfR	Membrane biofilm reactor
MBR	Membrane bioreactors
MD	Membrane distillation
MED	multi effect distillation
MQTT	Message Queuing Telemetry Transport
MIA	Modelling and integrated assessment
MOB	Mobile-organic biofilm,
Mobile RFD	Mobile rainwater-for-drinking
MoEYS	Memorandum of Understanding among the Ministry of Education, Youth and Sport
MPC	Model predictive control
MPs	Microplastics
MST	Microbial source tracking
MSU	Michigan State University
MVR	mechanical vapour recompression
MXC	Microbial electrochemical cells
NBS	Nature-based solutions
NGO	non-governmental organisation
NGS	Next generation sequencing
NOM	Natural organic matter
NPDES	National pollutant discharge elimination system
NPV	Net present value
NRW	Non-revenue water
NTP	Nansemond Treatment Plant
OT	Operational technology
PdNA	Partial denitrification anammox
PE	population equivalent
PFAS	Per- and polyfluoroalkyl substances
PI	Proportional integral
PPO	Proximal policy optimisation
PS	Particle separation
QMRA	Quantitative microbial risk assessment
qPCR	Quantitative polymerase chain reaction
RAC	Royal Academy of Cambodia
RAS	Return activated sludge
RFA	Rain for All
RFD	Rainwater-for-drinking
RL	Reinforcement learning
ROS	Resource-Oriented Sanitation
RPTWW	Reusing partially treated wastewater
RWHM	Rainwater harvesting and management
S2EBPR	Side-stream enhanced biological P removal
SaaS models	Software as a Service
SCADA	Supervisory control and data acquisition
SciML	Scientific machine learning
SFPUC	San Francisco Public Utilities Commission
SRT	Solids retention time
SSF	Subsurface flow
SSI	Sanitation sustainability index
STW	Shallow tubewells

SWP	State water project
SWWS	Small water and wastewater system
TES	Target enrichment sequencing
TEvap	Evapotranspiration tank
THM	Trihalomethanes
THP	Thermal hydrolysis processes
TSS	Total suspended solids
TW	Treatment wetlands
UASB	Up-flow anaerobic sludge blanket
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNS	Unified namespace
UVM	Untargeted viral metagenomics
UWWTD	Urban Wastewater Treatment Directive
VF	Vertical flow
VR	Virtual reality
WASH	Water, sanitation, and hygiene
WCEI	Water Circular Economy Index
WICER	Water in Circular Economy and Resilience
WOLL	water-oriented living lab
WRRF	Water resource recovery facilities
WSP	Water safety plan
WWTP	Wastewater treatment plant
WWTW	Wastewater treatment work



| 1 |

Climate resilience and water security

Water systems are entering a period in which familiar hydrological patterns are becoming a less certain guide to the future. Patterns of rainfall, runoff, recharge, and water quality are shifting, making the availability and reliability of water increasingly difficult to anticipate. Droughts, intense rainfall, flooding, salinisation, and pollution increasingly overlap within the same territories. Extreme events, including wildfires and major storms, may leave hydrological effects that persist after the immediate crisis, altering vegetation, soils, and the movement and quality of water. These pressures are especially severe where sources are already degraded, infrastructure is ageing, institutions are fragmented or communities face persistent inequalities in access. For many of these communities, water security depends on a combination of rainwater, springs, wells, streams, and local storage, each exposed in different ways to climatic variability.

The contributions in this section show that water security rests on more than availability alone. It also depends on quality, reliability, access, and the health of the ecosystems that sustain water resources over time. From this broader perspective, surface water, rainwater harvesting, water reuse, and natural storage are better understood as complementary parts of a diversified system. Groundwater has a quiet yet essential place within that system, since aquifer storage can help absorb seasonal and climatic variability and provide continuity when other sources become less dependable. Realising this potential requires careful assessment, protection of water quality and management that recognises the connections between aquifers, land use and surface water.

The chapters show how diversification becomes meaningful when it is translated into locally workable combinations. Water reuse can provide a more predictable source for agriculture, industry, and urban uses, while rainwater harvesting can ease pressure on centralised networks and strengthen preparedness at household and community scales. Decentralised systems extend this logic by retaining water and recovering resources closer to where they are generated. Nature-based solutions, treatment wetlands, and adaptive forms of urban drainage add another layer, restoring infiltration, storage, filtration, and flow regulation while also supporting biodiversity and environmental quality. Across these approaches, efficiency, adaptive monitoring, and risk-based planning help water systems respond before disruption becomes service failure. The balance among these options will inevitably differ across coastal areas, cities, and small water systems, where exposure, available capacity, and the practical realities of operation and maintenance shape what can endure. Their value therefore lies in how they are combined and adapted to place, rather than in applying a single approach everywhere.

These technical options can only deliver lasting resilience when they are grounded in the social and institutional realities of each place. Water insecurity is rarely shared equally, and communities with the least influence over infrastructure and investment decisions are often the most exposed to unreliable supply, declining water quality and climate-related disruption. This makes resilience inseparable from questions of access, responsibility, and voice. It matters who can rely on alternative sources, whose knowledge shapes decisions, who carries the costs of adaptation, and who is expected to operate and maintain the systems introduced. Bringing community participation, local experience and scientific evidence into planning from the outset can lead to responses that are more legitimate, durable, and fair. It also recognises that adaptation will take different forms across cities, coastal settlements, rural areas, and locally managed water systems.

Taken together, the chapters present climate resilience and water security as a shared systems challenge. Diversified supplies, protected catchments and aquifers, water reuse, natural processes, and flexible infrastructure all depend on sustained financing, monitoring, institutional learning, and public trust. The Specialist Groups and Clusters of IWA help connect these dimensions by bringing together expertise from across technologies, ecosystems, utilities, communities, and governance. Their collective contribution points beyond short-term responses to individual crises and towards water systems capable of learning, adjusting, and continuing to serve people under changing conditions. Ultimately, resilience will be measured not by how well a system performs under expected conditions, but by whether it can safeguard water, sustain services and reduce unequal burdens when those conditions no longer hold.

Key messages

Water security is strengthened through diversity. Different sources and forms of storage should be managed as a connected portfolio rather than as isolated assets.

Climate resilience depends on protecting and managing the full water system, from catchments, soils, and aquifers to treatment, reuse, and service delivery.

Effective solutions are rooted in place and shaped with communities, bringing scientific evidence together with long-standing local knowledge, lived experience, and cultural understanding.

Lasting resilience requires enabling institutions, with the governance, financing, monitoring and operational capacity needed to sustain services, reduce unequal burdens, and adapt as conditions change.

| 1.1 |

Climate resilience and water security

Authors: *Stevo Lavrnić, Maria João Rosa, and Blanca Jimenez on behalf of the Water Reuse Specialist Group*

Introduction

Water security is emerging as one of the most critical global challenges of the modern world, due to the combined effect of climate change, demographic growth, and pollution increase, all limiting water available for different uses. These changes (e.g. the melting of glaciers and loss of permafrost) directly affect water resources and their management (IPCC, 2019). One effect of the climate change is also a big alternation in the hydrological cycles, leading to less uniform precipitation distribution and more frequent periods of both droughts and extreme rain events leading to floods. These extremes are actually projected to increase with every degree of global warming (Caretta et al., 2022) and therefore they are a big concern for the water management sector. As a result, water professionals need to be aware of such impacts to define additional effects and set measures for their control or, even benefit from them when feasible.

Water reuse has drawn increasing attention as a proven instrument of resilience increase, since it gives value and uses water resources (e.g. treated wastewater, stormwater) that would otherwise be discharged as waste. There are numerous applications of this practice in various sectors (e.g. agriculture, industry, potable supply) in advanced settings (EPA, 2025a). However, despite technical feasibility and successful case studies, water reuse remains underexploited globally. Barriers include high capital and operating costs of advanced treatment and distribution infrastructures, regulatory and institutional fragmentation, public acceptance, and uncertainties around long-term health or ecological risks. The European Water Resilience Strategy states that safe water reuse needs to be at the heart of integrated water management in the EU, but this practice still has not reached its full potential (Water Europe, 2025). Currently, at the EU level only 2.4% of wastewater is being reused and there are major differences between Member States, the range being 0–89% (Directorate-General for Environment, 2023).

Therefore, this chapter aims to present insights on water security and resilience from the perspective of water reuse professionals. It seeks to highlight how experts and practitioners in the water reuse sector perceive the current challenges, opportunities, and barriers to integrating reuse into broader water management and resilience strategies.

Key terminology

- **Water reuse:** the planned use of treated wastewater for different purposes (e.g. agricultural irrigation, industrial processes)
- **Reclaimed water:** wastewater that has been treated to a quality suitable for a defined reuse purpose
- **Direct water reuse:** reclaimed water is conveyed directly from a treatment facility to the point of use, without first being discharged into another water body
- **Indirect water reuse:** reclaimed water is discharged into an environmental buffer (e.g. river, reservoir, aquifer), before being abstracted and used again; this buffer can provide additional treatment or storage.

Key insights

Advantages of water reuse

Water reuse practices can offer numerous advantages that directly contribute to climate resilience by enhancing water security. For example, treated wastewater represents a reliable source of water that can supplement traditional surface and groundwater supplies, and that can bridge the gap that exists between water availability and water needs. Its amount is not that climate dependent as it is with other water sources since reclaimed water is locally generated and controlled, granting communities greater autonomy and reducing vulnerability to climate-induced water scarcity (EEA, 2025). Advanced treatment technologies are able to ensure water quality fit for intended uses, and treated wastewater can be used for multiple purposes, such as irrigation, industrial processes, and even potable needs (EPA, 2025a; EEA, 2025).

Moreover, investments in water reuse infrastructure often cost less than alternatives such as building new reservoirs or desalination plants, providing cost-effective augmentation of water supplies. Moreover, water reuse supports sustainable economic prosperity by ensuring a steady water supply which is crucial for job creation and long-term business productivity (EPA, 2025b). It also reduces environmental remediation costs by lowering freshwater withdrawals and decreasing pollutant loads in natural water bodies (AFD, 2024, EEA, 2025).

Finally, water-dependent ecosystems (e.g. wetlands) are experiencing high stress due to reduced availability of natural water sources that are, in the cases of scarcity, often used to satisfy human needs. Therefore, water reuse can also contribute to biodiversity conservation (EPA, 2025c) and other opportunities by ensuring more reliable water availability despite droughts, floods, and shifting hydrological patterns (Water Europe, 2025).

Overall, the multi-dimensional benefits of water reuse can contribute to climate resilience, increasing robustness of systems and intensifying their ability to better respond and recover from climatic water stresses (Pistocchi et al, 2018).

Barriers for water reuse

Despite its clear benefits, water reuse is facing many obstacles, such as regulatory gaps, financing, and public perception.

A significant challenge is surely the lack of harmonised regulations for different reuse applications. Fragmented legislation across water, health, and agricultural authorities often creates conflicting standards or uncertainties that hinder investment and implementation of reuse projects (Maffettone and Gawlik, 2022) that, in the long-run, could help increasing the climate resilience. Excessively strict water quality criteria that do not reflect current scientific advances can limit reuse application unnecessarily (Maffettone and Gawlik, 2022). This kind of issue is also present in the EU, with a common legislative framework, and even though the EU supports water reuse in agriculture and issued a regulation in that field, some of the member states do not allow such a practice.

Water reuse projects can present high initial capital costs as well as perceived financial risks. Therefore, although reuse can be cost-effective long term, funding infrastructure development requires visible government or private-sector commitment and clear incentive mechanisms (AFD, 2023; Jordanian Ministry of Water and Irrigation, 2023). On the other hand, financing issues in urban reuse may be minimised by framing water reuse projects within climate contracts for the cities. Moreover, since water reuse is considered as an adaptation option for water crisis, mitigation and adaptation funds can be used to implement such projects (IPCC, 2022).

On the other hand, social acceptance remains a critical barrier due to psychological aversion and concerns about safety (Trudeau et al., 2022). Misinformation, lack of trust in treatment efficacy and cultural attitudes challenge public support. Effective engagement, transparency, and education are essential to mitigate these concerns (EU, 2020). Moreover, public perception issues in urban reuse may be minimised by flagship projects, e.g. the case of direct potable reuse for craft beer production in Lisbon, which was used to build the public trust on water reuse safety (Viegas et al., 2025).

Addressing these interlinked barriers through policy reform, economic tools, and stakeholder involvement is imperative to unlocking water reuse's full potential (EPA, 2025a), and a well-organised public campaign on water scarcity issues and potential problems regarding water distribution over the next decades, as well as increasing need for water resilience to be reached in the next future, might help with reducing these barriers and gaining more support for water reuse. The successful example of Singapore's programme shows how public engagement campaigns, stringent water quality regulations, and investments in cutting-edge treatment technology can work together towards promotion and wide application of water reuse (UNESCO and UNESCO i-WSSM, 2020).

Integrated resource management

Water reuse is an important part of a broader integrated and circular resource management. Reusing treated wastewater embodies circular economy principles by transforming waste streams into valuable resources, closing loops in water cycles, and reducing environmental footprints (UNESCO and UNESCO i-WSSM, 2020). This shift contributes to sustainability by minimising water extraction, one of the key barriers to reaching climate resilience. Therefore, to progress towards water resilience and water smartness,

water reuse must be considered side by side with the other water sources, as established in the new European Directive on Urban Wastewater Treatment and benchmarked regarding environmental and economic impacts.

Integrated resource management approaches require full collaboration across different reuse sectors (e.g. agriculture, industry), governance and communities (Water Europe, 2025), applying systems thinking and risk-based approaches ensuring that water reuse interventions support resilient and adaptable water management systems responsive to climate risks.

For example, water reuse performance as a function of water scarcity is a key aspect considered in the water smartness assessment framework adopted in the roadmap for creating and maintaining a successful WOLL (water-oriented living lab), produced within the Water4All Partnership which currently involves more than 25 WOLLs in Europe (Water4All Atlas of WOLLs, 2024).

Case studies

Water reuse has emerged as a critical strategy for improving climate resilience and water availability, particularly in regions facing escalating water scarcity and variable hydrological conditions due to climate change.

The Middle East is one of the most water-stressed regions globally, with limited renewable freshwater supplies exacerbated by population growth and climatic extremities (AFD, 2023). Jordan reuses around 90% of its treated wastewater, mixing it with freshwater from the Jordan Valley and storing a part of it in artificial storage basins (Jordanian Ministry of Water and Irrigation, 2023), before using it for agricultural irrigation. Similarly, in Abu Dhabi, water is reused on a large scale in the emirate, which, in 2023, reached the goal of using 80% of reclaimed water. That practice contributes to the preservation of rapidly depleting freshwater resources and lowers the need for seawater desalination (Global Water Award, 2024), while at the same time reducing energy demands.

In California, recurrent severe droughts have propelled large-scale water reuse efforts to augment increasingly unreliable traditional supplies. Los Angeles County through extensive water-reuse projects converts stormwater and treated wastewater into additional water source, reducing reliance on imported freshwater and bolstering climate resilience. Existing infrastructure is used to divert urban stormwater runoff into sanitary sewers for treatment, supplying non-potable and indirect potable uses. Moreover, capturing excess stormwater during heavy rain and enhancing groundwater recharge are strengthening even further the regional water security (EPA, 2025d).

Namibia's capital, Windhoek, has been one of the global successful examples of direct potable water reuse, using the Goreangab Water Reclamation Plant to treat municipal wastewater to drinking quality. The multi-barrier process, including non-treatment, treatment, and operational functions, ensures safety and reliability. The system is contributing up to 25% of the city's potable water (Lahnsteiner et al, 2024). Moreover, São Paulo, an economic hub of Brazil, has relied on large-scale industrial water reuse to sustain critical manufacturing sectors through the Aquapolo project. It treats sewage to supply industrial users and operates under long-term purchase agreements ensuring steady demand and financial viability. This practice enabled industries to maintain operations during severe droughts while alleviating demand on increasingly constrained potable water supplies (World Bank, 2025).

Singapore is one of the best global examples of water reuse as a key part of a comprehensive water management strategy addressing extreme land and water scarcity. Its NEWater initiative treats wastewater through a series of advanced technologies, producing high-quality reclaimed water used for industrial, commercial, and indirect potable applications. Approximately 40% of Singapore's water demand is met through reclaimed water, and it should reach 55% by 2060 (UNESCO and UNESCO i-WSSM, 2020). A promising urban example is that of the Lisbon WOLL in urban water reuse (Rosa et al., 2024). To fight negative effects of climate change, the city is increasing green areas that result in increased irrigation needs and reclaimed water may safely satisfy this additional demand.

The importance of these models for other drought-prone areas lies in the fact that they demonstrate how water reuse, when strategically implemented, can be effective in drought-proofing water supplies, reducing ecosystem stress, boosting climate resilience, and fostering adaptive water management under accelerating climate change conditions.

Recommendations

To fully apply potential for water reuse and to boost the climate resilience and water security, coordinated efforts in research innovation (e.g. treatment technologies) and policy development (e.g. water quality standards) are crucial. As water reuse applications expand, identifying priority themes is essential to improve its integration into complex water management, thus enhancing resilience to climate impacts.

Current treatment technologies do enable high-quality reclaimed water but are often connected to significant costs. Therefore, it is important to develop next-generation treatment methods that combine high contaminant removal efficiencies with lower energy and chemical inputs, reducing overall operational costs and environmental footprints (AFD, 2023). These innovations should be scalable for diverse reuse contexts, both small communities and large urban centres (IPCC, 2022). Nature-based solutions could be an important part of that focus, since they already provide different benefits (e.g. slow release of water stored) that increase climate resilience (EPA, 2025c) and are being successfully applied in the water reuse sector (Mancuso et al, 2023). Finally, digitalisation, real-time monitoring, and application of artificial intelligence should also be considered since they might help to optimise treatment processes and ensure safety at lower costs (Liu et al, 2025; Water Europe, 2025).

On the other hand, effective implementation of water reuse requires comprehensive planning and understanding of overall water balance as well as its vulnerability under current and future climate scenarios (IPCC, 2022). Therefore, integrated hydrological and socio-economic models at regional to basin scales should be developed for quantifying water security, incorporating reuse contributions and projections of climate-driven changes (Rosa et al., 2025).

Ensuring the safety of reclaimed water remains paramount to protecting public health and sustaining trust critical for reuse acceptance (AFD, 2024; Berti-Suman et al, 2023). Hence, it would be important for the future research strategies to focus on refining precise and easy-to-use risk assessment methodologies adapted to diverse reuse applications (Ribeiro and Rosa, 2024; Drei et al, 2025), but also on developing robust multi-barrier approaches that can reduce the risks (Drei et al, 2025).

However, supportive and coherent policies are essential at national and regional levels that recognise water reuse as a strategic measure within climate adaptation and water security policies (AFD, 2024). Clear water resource management plans and climate resilience frameworks should incorporate water reuse objectives, promoting multi-level governance mechanisms that foster collaboration among different stakeholders and that align reuse deployment with regional sustainability goals (EPA, 2025a). These should be based on scientific approach, but should also take into account practical experiences and obstacles that were encountered so far.

As said before, it would be important to harmonise regulations, reduceing fragmentation and uncertainty, as well as enabling permitting and cross-jurisdictional collaboration (Berti-Suman, 2023). Clear regulatory pathways that reduce investment risks and foster confidence are necessary for expanding water reuse infrastructure, but direct financial supports (e.g. grants, tax incentives) should be designed to target capital investments and operational costs of reuse infrastructures (UNESCO and UNESCO i-WSSM, 2020), considering real water costs in current and future climatic scenarios.

Conclusions

As climate change makes water resources scarcer and their quantity unpredictable around the world, reusing water is becoming an essential part of flexible water management. To fully unlock its potential, progress is needed in technology, science, and policy. Research should focus on developing new treatment methods, improving large-scale water security assessments, and creating better health-based risk systems. These efforts will make water reuse safer, more practical, and more efficient.

At the same time, water reuse should be included in broader resilience strategies, supported by clear regulations and a variety of incentives to encourage public acceptance and large-scale use. On that path, collaboration between researchers, policymakers, water utilities, and communities is crucial, and it should be supported by international knowledge sharing, leading to better decisions and adaptable governance systems that respond to changing climate conditions.

Unlocking the transformative potential of water reuse as a foundation for climate resilience and water security is imperative for sustainable water futures.

References

AFD (2023) Water reuse as strategic response to water stress in MENA countries. Agence Française de Développement.

Berti Suman, A., García-Herrero, L., Lavrnić, S., Sole, M. C., Toscano, A., and Vittuari, M. (2023). The advent of EU water reuse regulation in the Mediterranean region: policy and legislative adaptation to address non-conventional water resources utilization in agriculture. *Water International*, 48(7), 839–860. https://doi.org/10.1080/02508060.2023.2277619

Caretta, M.A., A. Mukherji, M. Arfanuzzaman, R.A. Betts, A. Gelfan, Y. Hirabayashi, T.K. Lissner, J. Liu, E. Lopez Gunn, R. Morgan, S. Mwanga, and S. Supratid, (2022): Water. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 551–712, doi:10.1017/9781009325844.006.

Directorate-General for Environment (2023) Water reuse: New EU rules to improve access to safe irrigation (https://environment.ec.europa.eu/news/water-reuse-new-eu-rules-improve-access-safe-irrigation-2023-06-26_en)

Drei, P., Mancuso, G., Lavrnić, S., Maffettone, R., Spizzirri, M., Merluzzi, L., Mastrantonio, A., Burla, P., and Toscano, A. (2025) A novel methodology to develop EU water reuse risk management plan in agricultural water distribution networks and crop irrigation systems, *Water Research X*, 28, , 100395, https://doi.org/10.1016/j.wroa.2025.100395.

EEA (2025) Climate-ADAPT, sharing adaption knowledge for a climate-resilient Europe (https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/water-recycling).

EPA (2025a) Water reuse action plan. (https://www.epa.gov/waterreuse/water-reuse-action-plan).

EPA (2025b) Case studies that demonstrate the benefits of water reuse. (https://www.epa.gov/waterreuse/case-studies-demonstrate-benefits-water-reuse)

EPA (2025c) Water reuse and nature-based solutions. (https://www.epa.gov/waterreuse/water-reuse-and-nature-based-solutions)

EPA (2025d) Water reuse case study: Los Angeles County, California (https://www.epa.gov/waterreuse/water-reuse-case-study-los-angeles-county-california)

European Union (2020) Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse. Official Journal of the European Union, L 177, 32–55.

Global Water Award (2024), https://globalwaterawards.com/2023-water-reuse-project-of-the-year/

IPCC (2019): Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–35. https://doi.org/10.1017/9781009157964.001.

IPCC (2022): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

Jordanian Ministry of Water and Irrigation (2023) Water sector policy for wastewater management and reuse (https://mwi.gov.jo/ebv4.0/root_storage/ar/eb_list_page/wastewater_management_and_reuse_policy-1.pdf).

Lahnsteiner, J., Honer, T., Ashipala, L., Nikodemus, K., Poussade, Y., and van Rensburg, P. (2024). Windhoek/Goreangab Direct Potable Water Reuse, Case Study Namibia. In: Lahnsteiner, J. (eds) *Handbook of Water and Used Water Purification*. Springer, Cham. https://doi.org/10.1007/978-3-319-78000-9_170.

Liu, Y., Mancuso, G., Petrotto, L., Lavrnić, S., Dong, Z., Tian ,Y., Zhang, J., and Toscano, A. (2025) AI-driven solutions in wastewater treatment and agricultural reuse systems: A comprehensive review. *Journal of Environmental Management*, 393, 127008, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2025.127008.)

Maffettone R., Gawlik B.M., *Technical Guidance - Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe*, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/590804, JRC129596.

Mancuso, G., Lavrnić, S., Canet-Martí, A., Zaheer, A., Avolio, F., Langergraber, G., and Toscano, A. (2023). Performance of lagoon and constructed wetland systems for tertiary wastewater treatment and potential of reclaimed water in agricultural irrigation, *Journal of Environmental Management*, 348, 119278, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2023.119278. (https://www.sciencedirect.com/science/article/pii/S0301479723020662)

Pistocchi, A., Aloe, A., Dorati, C., Alcalde Sanz, L., Bouraoui, F., Gawlik, B., Grizzetti, B., Pastori, M., Vigiak, O., The potential of water reuse for agricultural irrigation in the EU. A Hydro-Economic Analysis, EUR 28980 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-77210-8, doi:10.2760/263713, JRC109870

Pistocchi, A., Aloe, A., Dorati, C., Alcalde Sanz, L., Bouraoui, F., Gawlik, B., Grizzetti, B., Pastori, M., Vigiak, O., The potential of water reuse for agricultural irrigation in the EU. A Hydro-Economic Analysis, EUR 28980 EN, Publications Office of the European Union, Luxembourg, (2018), , doi:10.2760/263713, JRC109870

Ribeiro R., and Rosa M.J. (2024). The role of scenario-building in risk assessment and decision-making on urban water reuse. Water 16, 2674. https://doi.org/10.3390/w16182674

Rosa M.J., Ribeiro R., Viegas R., Oliveira M., Teixeira P., Figueiredo D., Lourinho R., Mendes R., Fernandes J., Alpalhão J., Coelho S.T., Vitorino D., Andrade D. (2024). B-WaterSmart solutions for Lisbon - Summary report. B-WaterSmart D2.15. https://b-watersmart.eu/results-downloads/water-smart-technologies-concepts/

Trudeau M., Hyung Choi S., Makarigakis, A.K. (2022) Water Reuse and Water Quality Challenges/ barriers. UNESCO and UNESCO iWSSM Policy Brief.

UNESCO and UNESCO i-WSSM (2020) Water reuse within a circular economy context (Series II). Global Water Security Issues (GWSI) Series - No2, UNESCO Publishing, Paris.

Viegas R.M.C., Figueiredo D., Mesquita E., Charrua S., Costa C., Lourinho R., Rosa M.J. (2025). Pilot-scale demonstration of advanced wastewater treatment for direct potable water reuse for beer production. *Separation and Purification Technology* 372, 133419. https://doi.org/10.1016/j.seppur.2025.133419

Water Europe (2025) Water Resilience Strategy. A Step towards a Water-Smart Society.

World Bank blogs (2025) Closing the loop: 'Water we doing on reuse?' (https://blogs.worldbank.org/en/water/closing-the-loop–water-we-doing-on-reuse–

| 1.2 |

Groundwater – a vital water-supply asset for climate-change resilience

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Key terminology

Aquifer: A geological formation capable of storing and transmitting sufficient quantities of groundwater for human use and environmental needs.

Climate-resilient development: Development pathways that integrate climate-change adaptation and mitigation with sustainable development objectives to reduce vulnerability and enhance resilience.

Conjunctive water use: The coordinated management and use of groundwater and surface-water resources to improve water-supply reliability and resource sustainability.

Groundwater recharge: The process by which water infiltrates through soil and rock and replenishes groundwater stored in aquifers.

Managed aquifer recharge (MAR): The artificial (man-made) recharge of aquifers using methods such as infiltration basins, riverbank filtration, or recharge wells to increase groundwater storage and improve water security.

Natural infrastructure: Natural systems and processes that provide services benefiting society, such as aquifers that store water, reduce drought risk, and support ecosystems.

Water security: The capacity of a population to safeguard sustainable access to adequate quantities and acceptable quality water for human well-being, economic development, and ecosystem protection.

Groundwater governance: The policies, institutions, regulations, and stakeholder processes used to manage and protect groundwater resources sustainably.

Groundwater for climate-change adaptation

Water is at the centre of climate challenge. As climate change alters precipitation patterns, intensifies hydrological extremes, and increases uncertainty in water availability, governments, utilities, and communities are being forced to rethink how water resources are managed. Across many regions, the growing frequency of droughts, periods of water scarcity, and damaging floods is exposing the vulnerability of water-supply systems that depend heavily on surface-water resources alone.

The IPCC Sixth Assessment Report (AR6) identifies water security as a critical component of climate-resilient development. Water-related risks are increasing in many parts of the world, affecting human health, food production, energy systems, economic development, and ecosystem integrity. In this context, adaptation is no longer simply a future requirement but a present necessity.

Among the various options available to strengthen water security, groundwater occupies a unique position. Groundwater stored within aquifers represents one of the largest forms of freshwater storage on Earth and has long provided a reliable source of water for cities, industries, agriculture, and rural communities. Yet despite its importance, groundwater often receives less attention than surface-water infrastructure in climate adaptation planning.

This relative neglect is increasingly difficult to justify. Aquifers function as natural reservoirs that can store water over long periods and provide supplies during droughts and other periods of stress. Their buffering capacity makes groundwater one of the most valuable natural assets available for strengthening resilience to climate variability and climate change.

As countries seek pathways towards climate-resilient development, groundwater should be recognised not merely as an alternative water source but as a strategic natural element that can help secure future water supplies, support economic activity, and sustain ecosystems under changing climatic conditions.

Groundwater as a natural climate element

Water-resource planning has traditionally focused on visible infrastructure such as dams, reservoirs, treatment plants, and distribution networks. These investments remain essential, but there is increasing recognition that natural elements can provide equally important services.

Aquifers are among the most significant forms of natural water elements. They store vast quantities of water underground, often protected from evaporation losses that can significantly reduce the effectiveness of surface reservoirs, particularly in arid and semi-arid regions. This storage function provides an important safeguard during periods when rainfall is below average or when surface-water supplies become unreliable.

Several characteristics make groundwater particularly valuable for climate adaptation. First, aquifers typically provide substantial storage capacity. In many geological settings, groundwater reserves accumulated over long periods can help buffer seasonal and interannual fluctuations in water availability. This capacity allows groundwater systems to respond more gradually to climatic variability than rivers and reservoirs. Second, groundwater often provides highly reliable supplies. Although well yields vary according to hydrogeological conditions, many aquifers can support substantial municipal, industrial, and agricultural demand. Third, groundwater quality is frequently suitable for potable use with limited treatment requirements. Natural filtration processes occurring within soils and geological formations often improve water quality and reduce exposure to some of the contamination risks commonly associated with surface waters. Finally, groundwater systems are generally less vulnerable to short-term climatic shocks. Floods, heatwaves, and extreme rainfall events can rapidly affect surface-water systems, while groundwater responses are typically moderated by the storage characteristics of aquifers.

These attributes make groundwater particularly important for strengthening resilience in urban areas, where water demand is concentrated and supply interruptions can have significant social and economic consequences.

Climate change and groundwater: a complex relationship

Although groundwater is often more resilient than surface water, climate change will inevitably affect groundwater systems. Understanding these impacts is essential for effective adaptation planning.

The relationship between climate change and groundwater differs fundamentally from the relationship between climate change and surface-water resources. Rivers, lakes, and reservoirs often respond rapidly to changes in precipitation and temperature. Groundwater systems, by contrast, are characterised by storage, delayed recharge, and longer response times. This distinction is important because it means that groundwater can provide stability during periods of climatic variability. However, it also means that changes in groundwater systems may emerge gradually and may not become apparent until years or even decades after climatic conditions have changed.

Current scientific understanding suggests that groundwater responses to climate change will vary considerably between regions and aquifer types. There is no single global pattern. In some areas, more intense rainfall events may increase recharge by promoting infiltration into aquifers. In others, higher temperatures, changing precipitation patterns, increased evapotranspiration, and longer dry periods may reduce recharge. Snow-dominated catchments may experience additional changes as declining snowpack and altered melt patterns affect groundwater replenishment.

The consequences will therefore depend on local hydrogeological conditions, land use, vegetation cover, and water-management practices.

Groundwater quality may also be affected. Extended droughts can increase the concentration of dissolved constituents in recharge waters, while intense rainfall events may enhance the transport of pollutants from the land surface into groundwater systems. Coastal aquifers face particular challenges as sea-level rise increases the risk of saline intrusion.

It has to be underlined that climate change is not the only pressure affecting groundwater resources. In many regions, unsustainable abstraction, land-use change, pollution, and inadequate governance already pose significant threats to groundwater security. In various conditions these pressures may have a greater impact on groundwater availability than climate change itself. Consequently, climate adaptation strategies must address both climatic and non-climatic drivers of groundwater stress.

Groundwater and urban water security

Urban areas are among the most vulnerable locations to water-related climate risks. Population growth, economic development, ageing infrastructure, and increasing competition for water are placing growing pressure on municipal water supplies.

Many cities continue to rely heavily on surface-water systems that are exposed to drought, changing river flows, sedimentation, and water-quality deterioration. Climate change is expected to increase uncertainty regarding the reliability of these supplies in many regions.

Groundwater can play a critical role in reducing this vulnerability. For many cities, groundwater already serves as an emergency reserve that can be mobilised during drought periods. However, its potential contribution often extends far beyond emergency use. Properly managed aquifers can form an integral component of diversified water-supply portfolios that combine surface water, groundwater, recycled water, and other sources. Diversification is increasingly recognised as a key principle of climate resilience. Water systems that depend on multiple sources are generally better able to cope with disruptions affecting any individual source.

Groundwater can also improve operational flexibility. Utilities with access to both surface-water and groundwater supplies can adjust production according to seasonal conditions, drought severity, water quality, and infrastructure constraints. This flexibility can significantly improve system reliability.

As cities expand, groundwater may also support decentralised approaches to water management. Large commercial developments, industries, and residential complexes can often utilise groundwater for non-potable applications such as landscape irrigation, cooling systems, and toilet flushing, thereby reducing pressure on centralised potable-water systems. Such approaches must be carefully regulated to ensure sustainability, but they illustrate the broader role groundwater can play in enhancing urban resilience.

Strengthening groundwater governance

If groundwater is to fulfil its potential role in climate adaptation, governance systems must evolve accordingly. Historically, groundwater management has often received less institutional attention than surface-water management. In many countries, monitoring networks are incomplete, abstraction data are limited, and management responsibilities are fragmented among different agencies.

Climate change highlights the need for more integrated approaches. Effective groundwater governance requires coordination across sectors, institutions, and administrative boundaries. Water-resource agencies, environmental regulators, municipalities, water utilities, agricultural authorities, and local communities all have important roles to play.

A central objective should be the development of comprehensive water-security strategies that assess the reliability of all available water sources under a range of future climate conditions. Such strategies should identify vulnerabilities, establish adaptation pathways, and define actions that can be implemented as conditions evolve.

Groundwater monitoring is particularly important. Reliable information on groundwater levels, recharge, abstraction, and water quality is essential for informed decision-making. Without adequate monitoring, managers cannot accurately assess resource status or evaluate the effectiveness of adaptation measures.

Licensing systems may also require adjustment. Historical abstraction permits often reflect assumptions about resource availability that may no longer be appropriate under changing climatic and socioeconomic conditions. Adaptive management approaches are therefore needed to align groundwater use with long-term sustainability objectives. The challenge is not simply technical. It is also institutional and financial. Managing natural features requires sustained investment, yet groundwater agencies often operate with limited resources compared with organisations responsible for conventional infrastructure. Addressing this imbalance is essential if groundwater is to contribute fully to climate resilience.

Enhancing recharge and managed aquifer recharge

One of the most promising opportunities for strengthening groundwater resilience lies in enhancing aquifer recharge. Managed aquifer recharge (MAR) refers to a range of techniques designed to increase groundwater storage by intentionally directing water into aquifers. These approaches can help capture water during wet periods and store it underground for future use.

MAR is increasingly attracting attention as a climate adaptation measure because it combines water storage with the advantages of natural underground reservoirs. Potential sources of recharge water include surplus river flows, stormwater, treated wastewater, and other available water resources. Depending on local conditions, recharge may occur through infiltration basins, riverbank filtration, recharge wells, or other engineered systems.

The benefits can be substantial. Underground storage minimises evaporation losses, improves water-supply reliability, and may provide additional water-quality benefits through natural filtration processes. However, successful implementation requires careful planning. Water quality must be appropriate for recharge, hydrogeological conditions must be suitable, and environmental impacts must be assessed. Long-term monitoring is also essential to ensure that recharge objectives are achieved.

Where conditions are favorable, MAR represents a practical example of how natural features can be combined with engineered solutions to improve climate resilience.

Protecting groundwater quality in a changing climate

Groundwater protection is an indispensable component of climate adaptation. The value of groundwater as a strategic reserve depends fundamentally on maintaining adequate water quality. Once contamination occurs, remediation can be technically difficult, expensive, and sometimes impossible within practical timescales.

Agriculture remains a major source of groundwater contamination in many regions. Excessive applications of fertilisers and pesticides can lead to long-term deterioration in groundwater quality. Urbanisation introduces additional pressures through wastewater discharges, inadequate sanitation systems, and industrial activities.

Mining operations, waste disposal sites, and other industrial developments may create further risks.

Climate change has the potential to amplify some of these challenges. More intense rainfall events can increase the mobilisation and transport of contaminants, while drought conditions may reduce dilution and concentrate pollutants. Protecting groundwater therefore requires proactive land-use management. Source protection zones around public water-supply wells and springs should be established and maintained. Land-use planning should explicitly consider groundwater vulnerability, and pollution-prevention measures should be integrated into broader climate adaptation strategies. Public awareness is also important. Because groundwater is hidden from view, its vulnerability is often underestimated. Greater engagement with communities, farmers, industries, and local governments can help build support for protection measures and promote sustainable practices. Ultimately, protecting groundwater quality is one of the most cost-effective investments available for enhancing long-term water security.

Learning from practice: Hanover and Lima

Experience from around the world demonstrates that groundwater can play a central role in resilient water-supply planning. The water-supply system serving the city of Hanover in Germany provides an example of long-term groundwater stewardship. The city's drinking-water supply is derived largely from protected groundwater sources located outside the urban area. Over many years, cooperative arrangements between water managers and agricultural stakeholders have helped reduce pollution risks while land-management measures have supported groundwater recharge and resource sustainability. The Hanover experience illustrates the importance of integrating catchment management, groundwater protection, and stakeholder engagement into a coherent strategy for safeguarding drinking-water resources.

Lima, Peru, offers a different but equally instructive example. Located in one of the world's driest coastal environments, the city has developed a water-supply strategy that combines surface-water and groundwater resources. Through conjunctive management, infrastructure investments, and recharge enhancement initiatives, groundwater has become a critical component of urban water security.

The lesson from both examples is clear. Resilient water systems rarely depend on a single source. Instead, they rely on diversification, adaptive management, and long-term investment in both natural and built infrastructure.

A call for strategic action

Groundwater is increasingly recognised as a cornerstone of water security in a changing climate. Yet its importance is still not adequately reflected in many adaptation strategies, urban development plans, or infrastructure investment programs. This situation must change. Water utilities should work closely with groundwater agencies to assess the status and resilience of available groundwater resources. These assessments should identify opportunities for conjunctive management, recharge enhancement, drought preparedness, and water-quality protection.

Governments should strengthen groundwater monitoring systems, improve governance arrangements, and provide greater investment in groundwater management and protection. Climate adaptation funding should recognise aquifers as critical natural infrastructure that delivers long-term public benefits. At the same time, groundwater protection must become a priority within broader land-use and environmental policies. Preventing contamination today is far more effective than attempting remediation in the future.

Most importantly, groundwater should be fully integrated into climate-resilient development pathways. As climate uncertainty increases, societies will need flexible and diversified water-resource systems capable of adapting to changing conditions. Groundwater offers precisely such flexibility. The challenge facing the water sector is not whether groundwater can contribute to climate resilience. The evidence from science and practice already demonstrates its value. The challenge is ensuring that groundwater receives the attention, investment, and protection necessary to fulfil its potential as one of the world's most important natural assets for water security.

As countries prepare for an increasingly uncertain climatic future, groundwater should move from the margins of adaptation planning to the center of water-security strategies. Properly managed and protected, it can provide the resilience needed to support communities, economies, and ecosystems for generations to come.

Bibliography

Doo P U et al. 2024 The impacts of climate change on groundwater quality: a review. *Science Total Environment* 912: 169241.

Dragoni W and Sukhija B S 2008 Climate change and groundwater: a short review. *Geological Society of London Special Publications* 288: 1–12.

Foster S and MacDonald A 2014 The 'water security' dialogue – why it needs to be better informed about groundwater. *Hydrogeology Journal* 22: 1489–1492.

Foster S 2022 The key role for groundwater in urban water-supply security. *Journal Water and Climate Change* 13 (10): 3566.

Foster S and Gathu J 2024 Groundwater use for urban water-supply in tropical Africa – operational situation and institutional perspectives. *Water International* 49: 782–791.

Olivier D W and Xu Y 2019 Making effective use of groundwater to avoid another water-supply crisis in Cape Town, South Africa. *Hydrogeology Journal* 27: 823–826.

Taylor R G et al. 2013 Ground Water and climate change. *Nature Climate Change* 3: 322–329.

UN-Water 2022 United Nations World Water Development Report – Groundwater: Making the Invisible Visible. UN-Water/UNESCO (Paris).

| 1.3 |

Nature-based solutions for resource-oriented sanitation systems

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Introduction

Municipal wastewater is a valuable but often overlooked source of water, organic matter, nutrients, and other valuable components such as energy and heat for reuse. However, municipal wastewater is currently managed as waste in a linear process of take, make, use, and dispose. As global water scarcity intensifies and the impacts of climate change become more pronounced, it is necessary to shift from this linear approach to a more holistic, circular management of resources to enhance climate resilience and ensure long-term water security (Schönborn and Junge 2021; van Hullebusch et al., 2021). Such a shift is critical: recovering water directly improves regional water security, while harnessing embedded energy and nutrients enhances climate resilience by reducing greenhouse gas emissions from conventional treatment and synthetic fertiliser production. Separating different streams (greywater, blackwater, and urine) at the source enables the concentration of specific compounds and thus a higher recovery rate (Larsen et al., 2013; Lehtoranta et al., 2022). Various treatment technologies focus on recovering the main components from each individual stream.

The IWA Specialist Group on Resource-Oriented Sanitation (ROS) focuses on sanitation systems that aim to push the boundaries of conventional sanitation solutions by:

- avoiding the transport of wastewater over long distances in sewerage systems; and
- facilitating the safe (re-)use of resources (water, nutrients, organic matter, energy)

in a way that minimises the use of non-renewable resources and negative environmental impacts.

For ROS systems to be sustainable, they must also protect and promote human health by:

- providing a clean environment and breaking the cycle of disease;
- being economically viable and socially acceptable; and
- being both technically and institutionally appropriate.

Nature-based solutions (NBS) have been shown to be used in various ways in ROS. In this chapter, we present examples to illustrate these applications.

Key terminology

Ammonia stripping:- physicochemical process used to remove ammonia nitrogen (NH_4^+-N) from wastewater by converting it into gaseous ammonia (NH_3) and transferring it from the liquid phase to the gas phase.

Blackwater: wastewater from toilets, containing urine, faeces, toilet paper, and flush water. It has a high concentration of organic matter, nutrients, and pathogens, and requires more intensive treatment than greywater.

Evapotranspiration systems (TEvap): soil- and plant-based systems that treat wastewater by promoting water loss through evaporation and plant transpiration. These systems also support nutrient uptake and biomass production.

Faecal sludge: semi-solid waste collected from onsite sanitation systems such as pit latrines and septic tanks. It requires treatment before safe disposal or reuse because of its high pathogen content.

Greywater: wastewater generated from household activities such as bathing, washing dishes, and laundry. It excludes toilet waste and is typically lower in organic load and pathogens, making it suitable for reuse after treatment.

Resource-oriented sanitation (ROS): a sanitation approach that focuses on recovering and safely reusing resources such as water, nutrients, organic matter, and energy from human waste streams. ROS systems aim to minimise environmental impact and promote circularity by avoiding long-distance wastewater transport and enabling local reuse.

Struvite precipitation: chemical process that recovers nitrogen and phosphorus from nutrient-rich wastewater by forming struvite crystals—magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$).

Urine-diverting toilets: sanitation systems that separate urine from faeces at the source, enabling targeted treatment and nutrient recovery. These toilets can be dry or water-based and are key components in ROS systems.

Vermicomposting: a biological process that uses earthworms and microorganisms to decompose organic waste, producing nutrient-rich compost suitable for agricultural use.

Insights in to nature-based solutions within resource oriented sanitation

While many NBS, such as treatment wetlands, focus primarily on pollutant removal from mixed wastewater for conventional reuse (e.g. agricultural irrigation), their application within ROS represents a different paradigm. In ROS, NBS are optimised for source-separated wastewater streams, enabling targeted recovery of nutrients, energy, and water within a circular economy framework. This distinction highlights how conventional, treatment-oriented NBS can be strategically adapted and upgraded for resource recovery and upcycling.

Greywater

Greywater, originating from sinks, showers, and washing machines, presents a significant opportunity for decentralised water recovery. Although various NBS can effectively process this stream (Cross et al., 2021), their implementation requires balancing technological maturity with urban spatial constraints. Conventional systems – such as horizontal, vertical, aerated, and free water surface wetlands – are well established for this purpose. However, their land requirements may pose a bottleneck. Consequently, space-saving innovations such as biological filtration systems and living walls are increasingly important for overcoming these barriers in dense urban environments.

Once recovered, this water can be used for non-potable applications such as toilet flushing, cleaning, or irrigation, significantly reducing potable water demand. Integrating greywater systems with blackwater recovery can eliminate the need for centralised sewage while supporting urban farming, biodiversity, and broader community resilience.

Blackwater and fecal sludge

Blackwater is toilet wastewater containing water, urine, faeces, and paper. Although produced in smaller volumes than greywater, it contains the highest levels of organic matter, nutrients, and pathogens (Paulo et al., 2019). In systems using urine-diverting toilets, blackwater nutrient levels are lower, as most nutrients originate from urine.

Due to its high organic content, blackwater is often treated anaerobically (e.g. in upflow anaerobic sludge blanket (UASB) reactors or anaerobic ponds) to produce biogas (Yang et al., 2023) with the resulting sludge and digestate upcycled as agricultural fertiliser (Wielemaker et al., 2018). The latter can also be produced from solid fractions in French vertical wetlands. For separated faeces, such as those from dry toilets, processes such as conventional composting, and vermicomposting (driven by earthworms and microbes) effectively capture nutrients to produce high-quality solid fertilisers and soil conditioners (Huang et al., 2020).

Conversely, blackwater can be treated in algae ponds to produce algal biomass for fertiliser, biostimulants, or bioenergy products (Segovia Bifarini et al., 2020). Similarly, to achieve true nutrient recovery in systems such as multi-stage wetlands and living walls, treatment must be combined with systematic biomass harvesting.

Urine

Urine can be separated from blackwater using urinals or urine-diverting toilets, with little or no water added. As it contains the highest nutrient concentration among all domestic wastewater streams, it is a highly valuable target for resource recovery, despite the potential presence of micropollutants and pathogens. While nutrients are often extracted using conventional physico-chemical processes such as struvite precipitation, ammonia stripping, and nitrification-distillation, NBS like high-rate algae ponds offer a powerful biological alternative. In these systems, nutrients are assimilated directly into algal biomass, which can then be harvested and upcycled into biofertilisers, biostimulants, biofuels, or high-value chemicals (Chatterjee et al., 2019). Ultimately, using these recovered, urine-derived products to fertilise broader urban NBS – such as street trees, green facades, and urban agriculture – closes the local nutrient loop, offsets synthetic fertiliser demand, and significantly reduces associated greenhouse gas emissions.

Mixed wastewater

In contexts where source separation has not been implemented, managing mixed municipal wastewater with NBS provides a robust and sustainable approach. Unlike isolated streams, mixed wastewater is diluted, which affects the design of NBS to extract nutrients and recover water. Various treatment wetlands, living walls, and evapotranspirative willow systems can be designed to reclaim water for safe agricultural reuse, directly reducing potable water stress. Furthermore, these systems capture carbon and diluted nutrients through rapid plant growth. Actively harvesting this biomass for use as compost or a renewable energy source enables circular resource recovery.

Case studies

Case study 1: integration of greywater reuse and urban farming in the example of KREIS-Haus

The inhabited living lab "KREIS-Haus", located in Feldbach, Switzerland, demonstrates a closed water and nutrient cycle based on greywater treatment and reuse for crop cultivation, alongside other sustainable building practices (Buehler et al., 2025a,c). First, rainwater is collected from the roof and treated through a series of filtration steps, including a particle filter, activated carbon, and UV LED, to produce drinking water for the shower and kitchen. Greywater from the sinks, shower, washing machine, and kitchen is collected and treated in-house with a low-tech, low-maintenance, and cost-effective biofilter system, then reused for laundry and irrigation of the rooftop garden. Excess treated greywater is returned to the greywater tank. When the greywater tank is full, it overflows into the overflow tank, which must be emptied manually when full. Thanks to the dry separation toilet, which collects urine and faeces separately, nutrients can be recovered from the faeces. The urine is collected in a tank beneath the house and processed into fertiliser using a pilot urine evaporation module. The urine is also stabilised in the tank and is therefore odourless. The faeces are transported to the room behind the toilet via a conveyor belt operated by a foot pedal, where they are processed into compost by vermicomposting. Both the compost and the urine-based fertiliser are used to grow plants in the rooftop garden (Figure 1.1).

By separating waste streams, reducing water use, and applying treated rainwater and greywater for specific purposes, the house achieves full water self-sufficiency, with rainwater as the sole source (Buehler et al., 2025a). The living-lab concept – where visitors experience the system – boosts acceptance and willingness to pay for sustainable practices. However, new organisational and maintenance models are needed for safe operation and scale-up (Buehler et al., 2025b).

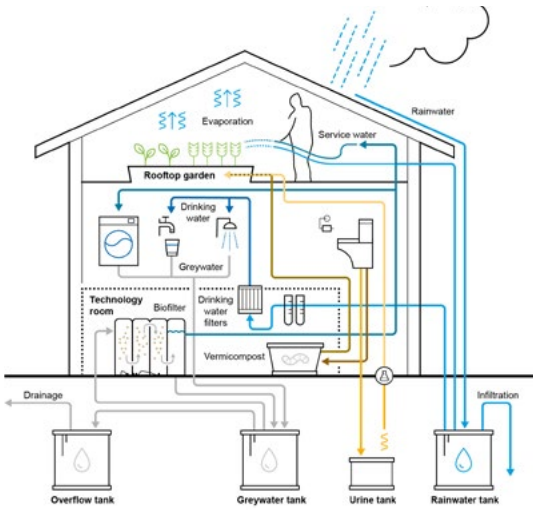


Figure 1.1: Concept of water and nutrient cycle in KREIS-Haus (Buehler et al., 2025c)

Case study 2: greywater and blackwater treatment in tropical climates

This case study comes from Brazil. The evapotranspiration tank (TEvap) is a low-cost, community-based solution for decentralised blackwater treatment. It consists of an impermeable tank with layered substrates and fast-growing plants (Figure 1.2). Blackwater enters at the bottom, flows upward through bricks and gravel for anaerobic digestion, then saturates sand and soil layers. Water is removed by evapotranspiration via capillary forces, wind, heat, and plant uptake, while nutrients are absorbed into biomass. Normally, no effluent leaves the system except under severe hydraulic overload.



Figure 1.2: Cross-sectional view of the TEvap showing the different substrate layers and the anaerobic chamber constructed with car tires (left); full-scale TEvap implemented in an urban area (right)

The EvaTAC system combines an adapted TEvap unit (CEvaT) with a horizontal-flow treatment wetland (HF-TW) for greywater treatment. It is proposed for use in urban areas, designed to avoid risks to users and to be fully integrated into the garden. The configuration aims to eliminate the sedimentation tank or septic tank as pre-treatment, which usually causes odour nuisance and excessive maintenance. The EvaTAC system (Figure 1.3) consists of two subsystems: an upflow evapotranspiration and treatment tank (CEvaT) with an inbuilt anaerobic chamber, followed by a HF-TW. The filter medium, covered with a layer of soil, serves as a support for the plants in the CEvaT unit (Magalhães Filho and Paulo 2022).

Twelve years of research show that the two units (CEvaT and HF-TW) complement each other, and the anaerobic chamber built into CEvaT can replace a pre-treatment unit, providing the system with stability and robustness. The full-scale system has operated continuously for 10 years without requiring sludge removal, which was a concern during development due to the expected high levels of solids and hair in the greywater. The microbiological profile indicated that each zone of the EvaTAC is unique and important for the development of different parts of the biogeochemical cycles within the system. The activity of the microbial community in one zone affects the environmental conditions and biofilm formation in the next zone, progressively influencing water quality parameters.





Figure 1.3: Pilot scale modules of the EvaTAC system (left); full scale EvaTAC system implemented in urban area (right)

Case study 3: treatment efficiency and agronomic potential of faecal sludge in India

A key challenge in using faecal sludge-based amendments is pathogen presence, especially helminth eggs, which resist conventional treatment. To address this, a study at the Devanahalli faecal sludge treatment plant (FSTP), Bengaluru, tested co-composting faecal sludge (FS) with municipal wet waste to reduce pathogens while maintaining nutrient balance. The nature-based FSTP operates without electricity, chemicals, or skilled labour and includes a screening chamber, feeding tank, anaerobic reactor, drying beds, and a co-composting unit (Consortium for DEWATS Dissemination Society 2020) (Figure 1.4).

A study in Bengaluru analysed FS from three NBS – unplanted and planted drying beds, and co-composting units. Thirty samples showed significant differences in nutrient content and physical properties among the treatment types: unplanted and planted drying beds retained higher levels of organic carbon and nitrogen, while co-composted FS contained more potassium due to the addition of organic waste. All samples met Indian compost standards for all parameters, including heavy metals, and the carbon-to-nitrogen ratios were within the agronomic range. These findings underscore the importance of treatment-specific characterisation to guide the safe and effective reuse of FS in agriculture (Ramakrishna and Patil 2025).

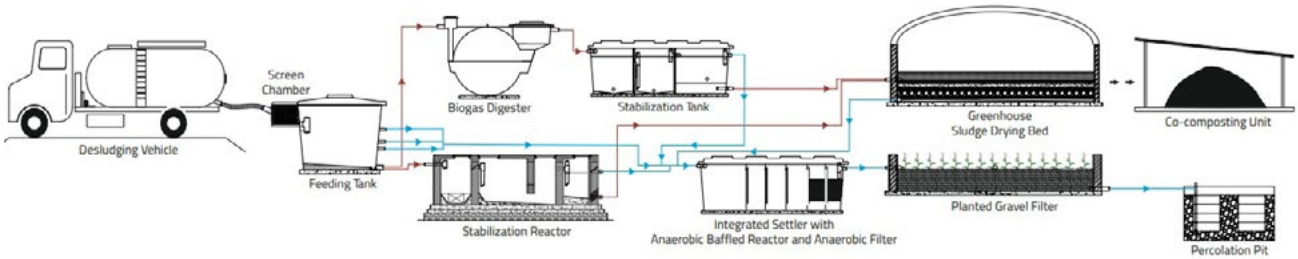


Figure 1.4: Scheme of Devanahalli faecal sludge treatment plant (Source: CDD India)

Co-composted FS was free of helminth eggs and had a balanced C:N ratio. Field trials showed improved yield and growth for beans and sweet potato over two seasons, confirming co-composting as a safe, nutrient-rich option for agricultural reuse (Ramakrishna et al., 2019).

In addition, greenhouse solar dryers (Figure 1.5, left) and a solar pasteurisation unit (Figure 1.5, right) over sludge drying beds were evaluated at four sites in India (Angul, Dhenkanal, Karunguzhi, and Devanahalli). Dryers maintained temperatures 7–8 °C above ambient and lower humidity, resulting in faster sludge drying, reduced drying bed requirements, and thus lower capital costs. Over 90 % of treated sludge samples were helminth egg-free due to elevated (Ramakrishna et al., 2023).





Figure 1.5: Greenhouse solar dryers, Angul (left) and solar pasteurisation unit, Dhenkanal (right)

Case study 4: transfer of indigenous knowledge in Korea

Inhabitants of ancient Korea understood the benefits of separately collecting and storing urine and faeces to improve soil fertility. Each household had private agricultural equipment for the independent collection of these materials for farm use. Furthermore, public sanitation facilities in ancient temples were designed to facilitate the composting of collected human waste for agricultural use (Hashemi et al., 2015; Han and Hashemi 2017).

In recent times, the development of innovative onsite sanitation systems has attracted renewed interest in the Republic of Korea. Hashemi and Han (2019) demonstrated an on-site sanitation system using a urine-diverting dry toilet to separate urine and faeces. The collected materials were nitrified and applied to soil for agricultural purposes. The findings showed that soils fertilised with a mixture of treated urine and faeces exhibited a nutrient release trend comparable to soils treated with commercial fertilisers.

A cost–benefit analysis of implementing source-separation sanitation systems in Korea divided the sanitation concept into pre-toilet, toilet, and post-toilet phases. The study highlighted that neglecting pre- and post-toilet infrastructure can mislead decision-making, resulting in increased capital and maintenance costs. Introducing wastewater source separation systems can yield economic benefits that offset these costs (Hashemi and Boudaghpour 2020). These findings were used to evaluate the sustainability of wastewater source separation systems in Korea using the Sanitation Sustainability Index (Hashemi 2020).

Case study 5: facilitating NBS for circularity – the COST Action Circular City

The COST Action Circular City (CA17133) promoted NBS to create circular economies in cities (Langergraber et al., 2021). The goal was to demonstrate how NBS can address resource depletion, climate change, and ecosystem degradation by preserving resources and reducing waste. The Action united over 600 scientists from more than 40 countries, including urban planners, architects, system designers, economists, engineers, and researchers from the social and natural sciences. The general objectives of the action can be viewed at https://www.youtube.com/watch?v=R3NXLb-W1pg (with subtitles in over 30 languages).

KEY RESULTS OF THE COST ACTION CIRCULAR CITY:

1. An overview of the state of the art in all working groups: Built Environment, Sustainable Urban Water Utilisation, Resource Recovery, Urban Farming, and Transformation Tools (https://iwaponline.com/bgs/pages/towards_circular_cities_special_issue).
2. A framework for addressing Urban Circularity Challenges with NBS, aiming to mainstream NBS for resource management (https://www.mdpi.com/journal/water/special_issues/water_circular_cities)
3. A graphic guidance tool presenting the framework (https:/toolbox.circular-city.eu/).

Additional outputs: training materials for city officials, the #mycircularcity photo competition, a self-paced online course, and a children's book in multiple languages (https://circular-city.eu).

KEY CONCLUSIONS FORM THE COST ACTION CIRCULAR CITY:

1. Cities must become more resilient to resource depletion, climate change, and ecosystem degradation
2. NBS deliver valuable ecosystem services for urban areas
3. Circular economy principles enhance NBS benefits
4. Plants are vital for green infrastructure and NBS but need irrigation, and rainwater is often insufficient
5. Drinking water should not be used for irrigation—treated water reuse is essential
6. Source-separated water, such as greywater, is ideal for irrigation and other non-potable uses

Recommendations

Mainstreaming NBS is no longer simply about deploying more treatment facilities; it requires integrating these technologies into ROS frameworks driven by circularity and active resource extraction. To accelerate this transition and build long-term climate resilience, stakeholders must prioritise the source separation of domestic wastewater streams. By preventing dilution at the source, this foundational step shifts the paradigm from conventional wastewater treatment to the targeted, highly efficient recovery of water, nutrients, and bioenergy. Policymakers are encouraged to support decentralised systems through enabling regulations, while industry actors should invest in user-friendly separation technologies and modular treatment units.

Integration of NBS with supporting technologies, such as struvite precipitation, solar drying, and biofiltration, can enhance system performance and safety. Researchers should focus on optimising hybrid systems and validating their long-term effectiveness across diverse climates and urban contexts. Demonstration projects like KREIS-Haus and EvaTAC show that combining ecological design with technical innovation can yield robust, low-maintenance solutions.

Finally, to unlock the full potential of NBS, legal frameworks and capacity building must evolve. Clear reuse guidelines, practitioner training, new organisational and maintenance models, and knowledge transfer – especially of indigenous and community-based practices – are essential. Collaborative efforts across sectors, supported by tools such as the Circular City framework, will help mainstream NBS and foster resilient, circular urban and rural sanitation systems.

Conclusions

NBS within ROS systems provide a transformative approach to wastewater management by enabling the recovery of water, nutrients, and organic matter while minimising environmental impact. Case studies from diverse contexts – ranging from urban living labs in Switzerland to decentralised treatment systems in Brazil – show that NBS can be technically robust, socially acceptable, and economically viable when adapted to local conditions and supported by appropriate infrastructure.

However, widespread implementation is still constrained by regulatory gaps, fragmented institutional support, and insufficient stakeholder awareness. To realise the full potential of NBS, coordinated efforts are required to integrate these solutions into urban planning, sanitation policy, and research agendas. By embracing circularity and fostering cross-sector collaboration, NBS can become a cornerstone of sustainable sanitation and resilient urban development.

References

Buehler D, Barmettler R, Schoenborn A, et al. (2025a) Off-grid rainwater and greywater treatment and reuse on household level: Conceptual approach and pilot operation at the KREIS-Haus demonstration case, Switzerland. *Water Reuse* 15:178–197. https://doi.org/10.2166/wrd.2025.104

Buehler D, Luethi L, Rousseau DPL, et al. (2025b) Drivers for the adoption of circular water systems at the building level in a high-income context. *Water Research X* 29:100416. https://doi.org/https://doi.org/10.1016/j.wroa.2025.100416

Buehler D, Vischer T, Junge R (2025c) A circular design concept for implementing sustainable building practices in the KREIS-Haus Living Lab, Switzerland. *Buildings* 15:. https://doi.org/10.3390/buildings15030409

Chatterjee P, Granatier M, Ramasamy P, et al. (2019) Microalgae grow on source separated human urine in Nordic climate: Outdoor pilot-scale cultivation. *Journal of Environmental Management* 237:119–127. https://doi.org/https://doi.org/10.1016/j.jenvman.2019.02.074

Cross K, Tondera K, Rizzo A, et al. (2021) Nature-Based Solutions for Wastewater Treatment: a series of factsheets and case studies. IWA Publishing, London

Han M, Hashemi S (2017) Sanitation revolution: From waste to resource. *Desalination and Water Treatment* 91:305–310. https://doi.org/10.5004/dwt.2017.20605

Hashemi S (2020) Sanitation sustainability index: a pilot approach to develop a community-based indicator for evaluating sustainability of sanitation systems. *Sustainability* 12, 6937.

Hashemi S, Boudaghpour S (2020) Economic analysis and probability of benefit of implementing onsite septic tank and resource-oriented sanitation systems in Seoul, South Korea. *Environmental Technology & Innovation* 18:100762. https://doi.org/https://doi.org/10.1016/j.eti.2020.100762

Hashemi S, Han M (2019) Field evaluation of the fertilizing potential of biologically treated sanitation products. *Science of the Total Environment* 650:1591–1598. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.09.009

Hashemi S, Han M, Kim T, Kim Y (2015) Innovative toilet technologies for smart and green cities. 873–879, in Proceedings of 8th Conference of the International Forum on Urbanism (IFoU), Incheon, 22 June–24 June 2015, MDPI: Basel, Switzerland, doi: 10.3390/ifou-E013. https://doi.org/10.3390/ifou-e013

Huang K, Xia H, Li F, Bhat SA (2020) Recycling of municipal sludge by vermicomposting. . In: Bhat SA, Vig AP, Li F, Ravindran B (eds), *Earthworm Assisted Remediation of Effluents and Wastes*. Springer Singapore, Singapore, pp 55–67.

Langergraber G, Castellar JAC, Andersen TR, et al. (2021) Towards a cross-sectoral view of nature-based solutions for enabling circular cities. *Water*, 13: 2352 13:2352. https://doi.org/10.3390/W13172352

Larsen TA, Udert KM, Lienert J (2013) Source separation and decentralization for wastewater management. *Water Intelligence Online*, 12: 10.2166/9781780401072.

Lehtoranta S, Laukka V, Vidal B, et al. (2022) Circular economy in wastewater management—the potential of source-separating sanitation in rural and peri-urban areas of Northern Finland and Sweden. *Frontiers in Environmental Science*, 10: 804718. doi: 10.3389/fenvs.2022.804718

Magalhães Filho FJ, Paulo P (2022) Chapter 7 - Phytoremediation as a modular approach for greywater treatment. In: Kaur Brar S, Kumar P, Cuprys A (eds), *Modular Treatment Approach for Drinking Water and Wastewater*, (eds). Elsevier, pp 107–128

Paulo PL, Galbiati AF, Magalhães Filho FJC, et al. (2019) Evapotranspiration tank for the treatment, disposal and resource recovery of blackwater. *Resource Conserv and Recycling*, 147: 61–66. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.04.025

Ramakrishna G, Hiranjya T, Krishna K, Ganapathy PG (2023) Greenhouse solar dryers: A cost-effective solution to ensure safe application of faecal sludge in agriculture. Consort DEWATS Dissem India Indian Inst Sci

Ramakrishna G, Patil B (2025) Characterisation of faecal sludge from different nature-based treatment processes for agricultural application. *Sustainability* 17(13): 5683; https://doi.org/10.3390/su17135683

Ramakrishna G, Shettigar NA, Ramakrishna PVR, Shamanna G (2019) Evaluation of co-composted faecal sludge application in agriculture. *WIT Transactions on Ecology and the Environment*, 238:701–711. https://doi.org/10.2495/SC190601

Schönborn A, Junge R (2021) Redefining ecological engineering in the context of circular economy and sustainable development. *Circular Economy and Sustainability* 1:375–394. https://doi.org/10.1007/s43615-021-00023-2

Segovia Bifarini MA, Žitnik M, Griessler Bulc T, Krivograd Klemenčič A (2020) Treatment and re-use of raw blackwater by *Chlorella vulgaris*-based system. *Water* 12, (10), 2660

van Hullebusch ED, Bani A, Carvalho M, et al. (2021) Nature-based units as building blocks for resource recovery systems in cities. *Water* 13:3153. https://doi.org/10.3390/W13223153

Wielemaker RC, Weijma J, Zeeman G (2018) Harvest to harvest: Recovering nutrients with New Sanitation systems for reuse in urban agriculture. Resource Conservation and Recycling 128:426–437. https://doi.org/https://doi.org/10.1016/j.resconrec.2016.09.015

Yang S, Li Z, Wang X, et al. (2023) Research progress of enhanced methane production by anaerobic digestion of blackwater. *Journal of Water Process Engineering* 53:103719. https://doi.org/https://doi.org/10.1016/j.jwpe.2023.103719

| 1.4 |

Nature-based solutions in small water and wastewater systems

Authors: Inga Herrmann, Stevo Lavrnić and Débora Boratto on behalf of the Small Water and Wastewater Systems Specialist Group

Introduction

Small water and wastewater systems (SWWS) play a crucial role in ensuring universal access to safe water and sanitation and to achieve SDG6 targets (Saadatinavaz et al., 2024). Not all communities can be connected to centralised networks, yet everyone requires reliable, clean, and healthy water and sanitation services. Due to limited economies of scale, providing high-quality services in areas that depend on small systems is often more costly. These decentralised solutions face persistent challenges such as insufficient maintenance, limited inspection, inadequate or absent treatment, and weak management of treatment facilities. Consequently, small systems may contribute to poor sanitation performance, low drinking water quality – especially where households rely on private wells of uncertain quality – and risks to human health and the environment. Inadequate wastewater treatment also degrades local receiving waters, bathing areas, and drinking water sources. In response to these challenges, the European Union is currently introducing stricter requirements for individual systems through the recast Urban Wastewater Treatment Directive (UWWTD).

Despite these challenges, SWWS also offer significant opportunities. They represent a vital component of the global sanitation landscape, especially in regions where centralised, piped systems are unaffordable or unsustainable. Even in high-income countries, maintaining large centralised systems has become increasingly complex and costly. Small, decentralised systems make it possible to implement more sustainable and innovative approaches tailored to local conditions. At small scales, it is not only feasible but often essential to promote the reuse of treated water and wastewater, helping to reduce overall water demand and close local water loops. Furthermore, nutrient recovery from wastewater can be achieved more easily at small scales, turning waste into a valuable resource.

Among these decentralised approaches, nature-based solutions (NBS) – engineered systems that harness natural processes – are particularly well suited for SWWS (e.g. Valipour et al, 2016). Examples include treatment wetlands (TW) for the treatment of wastewater and sludge. TW can be effective, resilient, and energy-efficient solutions, delivering reliable treatment performance while providing additional environmental and social co-benefits. TW are especially valuable for locally treating domestic wastewater from households, helping to protect nearby water sources from contamination and directly contributing to local water security.

Key terminology

NBS: nature-based solutions, human-made infrastructures that mimic natural processes and use them to provide benefits for human well-being and biodiversity.

SWWS: small water and wastewater systems, serving individual houses, a cluster of houses or a small community or village.

TW: treatment wetlands, engineered systems using natural processes for the treatment of wastewater or sludge.

Key insights

NBS address challenges related to both water quantity and quality by restoring natural processes such as filtration, sedimentation, infiltration, and evapotranspiration. Beyond their core treatment function – particularly important in SWWS – NBS have the potential to provide multiple co-benefits, including habitat creation, biodiversity enhancement, and carbon sequestration. Their low energy requirments, reduced chemical use, and modest maintenance needs make

them especially suitable for decentralised contexts. Because they can be operated and maintained locally, NBS can help strengthen community ownership, build capacity and support circular-economy practices. Together, these characteristics contribute to long-term sustainability and resilience in the face of climate variability and ecosystem degradation.

TW as a widely applied form of NBS, provide numerous advantages when used in SWWS. They are especially appropriate for rural and peri-urban areas, where decentralised solutions are often the most viable option. TW systems can offer strong treatment performance, and although their footprint is larger than that of conventional wastewater treatment plants, this is often acceptable in rural settings. Moreover, when designed as compact systems, their land requirements can be significantly reduced. They are inherently robust, require less maintenance than many conventional technologies (e.g. package treatment plants), and tolerate fluctuations in loading, which are common in small systems. In addition, their operation and maintenance do not depend on highly trained operators to the same extent as many conventional treatment technologies. TW can provide stable and reliable treatment performance, although efficiency can vary with climatic conditions. They can also produce effluent quality suitable for water reuse and support resource recovery, for example by harvesting plant biomass for soil improvement in local agriculture.

Intensification of treatment wetlands has emerged as an interesting approach for SWWS, aiming to increase treatment capacity and reduce system footprint where constraints or higher performance requirements apply. Strategies include artificial aeration and recirculation (e.g. Huma et al., 2017); use of reactive media, reciprocation (tidal-flow operation) to enhance subsurface oxygen transfer, and partial saturation to improve nitrogen removal (Dotro et al., 2017); bioaugmentation to enhance removal of pharmaceutical compounds (e.g. Sharma et al., 2025); and functionalised plants with enhanced pollutant uptake (e.g. Valipour et al., 2015). Footprint reduction can also lower capital investment costs, improving competitiveness with other treatment technologies.

Hybrid systems, combining NBS with intensive treatment units such as membrane bioreactors or UV disinfection, represent another key development. These configurations achieve high contaminant-removal efficiencies where sensitive receiving waters or water-reuse applications require stringent effluent standards. Hybridisation maintains the environmental and operational advantages of NBS while ensuring consistent performance under fluctuating loads or tight regulatory standards. By buffering hydraulic peaks and stabilising influent loads, the NBS component enhances system resilience and reduces operational pressure on mechanical units.

Advanced modelling and AI-based tools can increasingly support the planning and operation of NBS. They can simulate and predict system behaviour under varying climatic conditions, hydraulic loading, or pollutant concentrations, and can inform decisions on design, configuration, and siting within a watershed to maximise the system performance and increase ecosystem benefits. These tools can also predict and quickly address potential malfunctioning – such as clogging or extreme-weather impacts – thus supporting long-term reliability and climate-resilient water management.

One important emerging trend in the application of TW within small water and wastewater systems is their growing adoption in cold regions. While traditionally perceived as challenging environments for biological treatment, recent research has shown that constructed wetlands can perform reliably even under prolonged low-temperature conditions. In sub-arctic Sweden, a French wetland adaptation (Figure 1.6) has demonstrated stable removal efficiencies for key parameters such as BOD and suspended solids, even at temperatures below –30°C (unpublished data). In the Arctic, relatively simple NBS are used to treat wastewater in the Canadian Arctic and rural Alaska (Jensen et al., 2025). These examples highlight that NBS can be viable options even in cold climates.

NBS in South America, particularly Brazil, reveal another emerging trend. Brazil's rapid expansion of wastewater services – driven by national goals to increase service coverage – has highlighted the value of TW as cost-effective, scalable solutions. For settlements below 10,000 population equivalent (PE), where installation and long-term operation of conventional systems pose major financial challenges, TW offer advantageous lifecycle performance. In this setting, while capital expenditure (CAPEX) may not always be lower, TW frequently outperform traditional systems in terms of net present value (NPV) due to lower operational and maintenance costs.

Adoption and dissemination trends vary significantly worldwide. TW are well established in rural France, where ca. 4,000 systems were already operating by 2017 (Lombard-Latune et al., 2017), and they are gaining prominence in Brazil. However, in countries such as Sweden – despite large land availability– their implementation has not yet begun. This limited uptake can be linked to a combination of factors, including low awareness and lack of knowledge about TW among utilities, and insufficient regulatory support. Strengthening knowledge exchange, updating regulations, and expanding training for utilities and authorities are essential to accelerate wider adoption.

Examples of NBS in small water and wastewater treatment systems

Examples of NBS applied as SWWS can be found worldwide, addressing diverse treatment needs and operational contexts. The cases below illustrate how NBS can function as passive, robust, and cost effective solutions for local wastewater and sludge management – from Arctic communities to subtropical regions and agricultural landscapes.

In Fort Good Hope in the Canadian Arctic, wastewater is collected by trucks from household holding tanks and transported to a decentralised NBS treatment facility (Figure 1.6). There, the wastewater is treated in a soil based infiltration system, where it percolates through naturally permeable soils and undergoes physical, chemical, and biological purification. Despite harsh climatic and operational conditions, this passive system has performed satisfactorily for more than 20 years (Boratto et al., 2025; Boratto et al., under review), demonstrating the longevity and resilience of NBS in extreme environments where site conditions allow.

Agricultural runoff also represents an important wastewater stream requiring decentralised treatment. A farm wetland near Bologna, Italy, treats surface runoff from a 12.5 ha agricultural area. Operational since 2000, the system continues to demonstrate high removal efficiencies for traditional pollutants (e.g. suspended solids, nutrients) (Lavrnić et al., 2020) as well as emerging contaminants (Buscarolli et al., 2024). In addition to improving water quality, the wetland attenuates peak flows, reduces downstream flood risk, and restores natural hydrological functions through groundwater recharge and enhanced soil water retention.

In Brazil, sludge treatment wetlands – designed for long term storage and mineralisation of excess and fecal sludge – are increasingly adopted as a practical way to enable septage treatment in areas not served by centralised sewer networks. By reducing transport distances and offering robust long term stabilisation, these systems are proving essential for extending wastewater service coverage in an affordable manner. In Descanso, in southern Brazil, sludge from individual septic tanks is treated in a reed bed system (Figure 1.6), serving around 8,000 PE. The water utility is responsible for transporting the sludge to the treatment unit. In operation since 2024, the system provides reliable treatment with minimal operational demands, illustrating how NBS can support rural utilities in managing decentralised sanitation safely and efficiently.

A wider range of full scale Brazilian applications further demonstrates the versatility of TW. Aerated wetlands have been implemented to upgrade long standing up-flow anaerobic sludge blanket (UASB) systems serving around 6,000 PE, consistently achieving chemical oxygen demand (COD) concentrations below 50 mg/L and full nitrification–denitrification. French type vertical flow systems for raw wastewater are being constructed for around 2,500 PE, offering a cost effective solution where treatment requirements are moderate (C. Platzer, personal communication, November 2025).

A persistent challenge across these cases is the difficulty of comparing NBS with conventional technologies. Limitations in monitoring data and the tendency to focus on CAPEX rather



Figure 1.6 Examples for use of nature-based solutions in small wastewater systems: Sludge treatment wetlands in Descanso, Santa Catarina, Brazil, 2024, credits: Wetlands Construídos Ltda (left), wastewater treatment facility in Fort Good Hope, Northwest Territories, Canada, 2024, credits: Débora Boratto (upper right), and pilot-cale French wetland in sub-arctic Sweden, 2024, credits: Peter Rosander (lower right).

than lifecycle costs can mask the true value of NBS, as their broader co benefits often remain unquantified or undervalued (C Platzer, personal communication, November 2025). Together, these examples illustrate the adaptability of NBS and their potential to provide sustainable, low operation cost treatment solutions for wastewater and sludge management across diverse climatic, geographic and socio-economic settings.

Recommendations

To ensure consistency and reliability in the implementation of NBS as SWWSs, it would be good practice to establish clear design and performance criteria that can be used by practitioners and policymakers. Although NBS are often tailored to local environmental and social conditions, the planning, construction, and management of SWWSs share several common elements. Developing practical, evidence-based guidelines would support wide-scale adoption of NBS and help ensure that systems are both effective and sustainable across diverse contexts. Such standards should be sufficiently flexible to accommodate local variability, while remaining rigorous enough to guarantee that essential treatment outcomes are achieved.

Another important aspect when considering wide-scale application of NBS as SWWS is policy. The competent authorities should integrate NBS and SWWSs in general into national water quality and resilience frameworks to formalise their use and encourage broader adoption, especially in the context where they are much more applicable compared to traditional engineered systems. These policies should particularly consider different benefits that NBS can provide, such as improved ecosystem health, resilience to climate change, and their societal role. Regulations should incentivise the adoption of NBS and demonstrate how they can provide reliable and cost-effective alternatives to conventional systems, while also aligning with national sustainability goals.

Apart from policy, an important incentive for the uptake of NBS as SWWS are targeted funding schemes that recognise the full spectrum of benefits offered by these solutions. Financial mechanisms should go beyond the primary function of water quality and quantity management, but they should incorporate additional ecosystem services such as carbon sequestration, biodiversity enhancement, and climate adaptation, or, in other words, holistic environmental, social, and economic value. Funding should also prioritise the scalability and long-term viability of projects, ensuring that smaller communities, which can especially benefit from NBS application, can access the resources they need.

The implementation of NBS requires expertise from a variety of disciplines, including ecology, hydrology. and engineering. Promoting multi-disciplinary collaboration among researchers, practitioners and policymakers can ensure that NBS are appropriately designed, implemented and managed, which is a key to long-term success. Moreover, local stakeholders, including communities, farmers and technicians should be consulted in every step of the way to increase their ability to manage and maintain NBS systems effectively. Engaging stakeholders early in the planning and decision-making processes fosters trust, ensures that the solutions meet local needs, and increases the likelihood of long-term success. Capacity building through education and training programmes can help stakeholders better understand the benefits and limitations of NBS, enabling informed decision-making and fostering collaboration across sectors. Public awareness campaigns can further strengthen acceptance by highlighting the role of NBS in improving water quality, increasing resilience and supporting biodiversity.

Conclusions

Nature-based Solutions (NBS), and treatment wetlands (TW) in particular, represent a set of approaches that can complement existing water and sanitation strategies in small communities. This contribution has shown that NBS can address both water quantity and water quality challenges by making use of natural processes to achieve treatment, while also offering additional ecological and social benefits. Their comparatively low energy requirements, modest maintenance needs, and relative operational simplicity make them suitable candidates for decentralised contexts, especially where conventional engineered systems may be difficult to operate sustainably.

The examples presented demonstrate that NBS can function effectively under a wide range of climatic, geographic, and socio economic conditions. These cases highlight the adaptability of TW and their potential to provide reliable treatment where decentralised solutions are needed. They also illustrate that, when assessed over their full lifecycle, NBS can be cost competitive with conventional systems in certain contexts.

However, NBS remain unevenly implemented across regions. Limited awareness, gaps in technical capacity and regulatory frameworks that do not yet fully recognise NBS can hinder adoption. Addressing these barriers will require clearer design and performance criteria, supportive policy environments, appropriate financing mechanisms and capacity building for utilities, practitioners, and authorities.

Looking ahead, further research and implementation efforts should focus on long-term performance monitoring across different climates and system configurations, quantifying co-benefits, integration with digital tools for adaptive operation and improved governance models, empowering communities, and ensuring sustained operation and maintenance.

Overall, NBS offer a set of approaches that can support progress toward SDG 6 and enhance resilience in small water and wastewater systems. Their broader integration into the water sector will depend on continued research, practical experience, and the development of governance and funding structures that ensure long term performance and sustainability.

References

Boratto, D., Kurylyk, B. L., and Jamieson, R. (2025). Modeling a rapid infiltration basin for wastewater treatment in the Arctic under various operating conditions. *Journal of Contaminant Hydrology*, 273, 104601. https://doi.org/10.1016/j.jconhyd.2025.104601

Boratto, D., Huang, Y, Johnston L., Lake C., Somers L., Kurylyk B., and Jamieson, R. (under review). Hydrological and microbial dynamics in an Arctic wastewater infiltration system. Vadose Zone Journal, e70078. https://doi.org/10.1002/vzj2.70078. Buscaroli E., Lavrnić S., Blasioli S., Gentile S.L., Solimando D., Mancuso G., Anconelli S., Braschi I., Toscano A. (2024) Efficient dissipation of acetamiprid, metalaxyl, S-metolachlor and terbuthylazine in a full-scale free water surface constructed wetland in Bologna province, Italy: A kinetic modeling study. *Environmental Research* 247, 118275, https://doi.org/10.1016/j.envres.2024.118275.

Dotro G., Langergraber G., Molle P., Nivala J., Puigagut J., Stein O., von Sperling M (2017) *Treatment wetlands*, volume 16, IWA Publishing https://doi.org/10.2166/9781780408774

Huma I., Ilyas M. (2017) Intensification of constructed wetlands for land area reduction: a review. *Environmental Science and Pollution Research* 24(13), 12081–12091, doi: 10.1007/s11356-017-8740-z

Jensen P. E., Boratto D., Rossi P. M., Velmitskaya M., Øverjordet I. B., Andradóttir H. Ó., ... and Jamieson R. (2025). The status of domestic wastewater treatment in the Arctic. *Environmental Science: Advances*, 4(9), 1373–1402. https://doi.org/10.1039/D5VA00082C

Lavrnić S., Nan X., Blasioli S., Braschi I., Anconelli S., Toscano A. (2020) Performance of a full scale constructed wetland as ecological practice for agricultural drainage water treatment in Northern Italy. *Ecological Engineering* 154, 105927, https://doi.org/10.1016/j.ecoleng.2020.105927.

Lombard-Latune R, Molle P (2017) Constructed wetlands for domestic wastewater treatment under tropical climate. Research Report, Agence française pour la biodiversité, hal-03242993.

Saadatinavaz, F., Alomari, M. A., Ali, M., and Saikaly, P. E. (2024). Striking a balance: decentralized and centralized wastewater treatment systems for advancing Sustainable Development Goal 6. *Advanced Energy and Sustainability Research*, 5(10). https://doi.org/10.1002/aesr.202400097

Sharma S., Thakur A., Pathela A., Rau R., Jha O., Raj Sharma N. (2025) Innovative approaches for performance enhancement of constructed wetlands. *Indian Journal of Microbiology* 65(3):1421–1440, https://doi.org/10.1007/s12088-025-01458-z.

Valipour A., Ahn Y.-H. (2015). Constructed wetlands as sustainable ecotechnologies in decentralization practices: a review. *Environmental Science and Pollution Research*, 23(1), 180–197. https://doi.org/10.1007/s11356-015-5713-y

| 1.5 |

Climate-resilient coastal sanitation: transforming marine outfall systems

Authors: *Lu Chang on behalf the Marine Outfall Systems (Joint IAHR/IWA)*

Introduction

Marine outfall systems (MOS) can take the role of adaptive infrastructure for coastal water security and ocean protection. Marine outfall systems are transitioning from static "end-of-pipe" infrastructure to dynamic, climate-resilient assets that integrate water security, public health, and ocean stewardship. As coastal zones face rising sea levels, intensifying storms, and altered stratification patterns, modern outfalls must combine adaptive hydraulic design, real-time digital monitoring, and risk-based operational protocols to protect millions of coastal residents while safeguarding marine ecosystems.

Key insights

Sea level rise reshapes hydraulic fundamentals

Traditional gravity-driven outfall designs assume stable mean sea levels. However, projections indicate a global rise of 0.3–1.2 m by 2100, with higher rates in Southeast Asia and Pacific island nations. This threatens:

- Treatment plant operations: Reduced hydraulic head and tidal backwater effects can overwhelm collection systems
- Storm resilience: Compound high-tide/storm-surge events may exceed design capacity.

ADAPTIVE RESPONSE

Modern systems employ hybrid-dynamic designs with variable-speed pumping stations that override gravity systems during extreme tidal events. Subsea pipelines now use high-density polyethylene (HDPE) reinforced with articulated concrete mattresses to prevent seabed liquefaction and scour damage during centennial storm events. These adaptations are no longer optional – they are design prerequisites for coastal water security.

Climate-driven stratification demands smart mixing

Warming oceans intensify thermal stratification, creating density barriers (pycnoclines) that trap wastewater plumes at suboptimal depths. If plumes sink too deep, they impact benthic ecosystems; if they surface too rapidly, they threaten coastal recreation and shellfish aquaculture.

ADAPTIVE RESPONSE

Next-generation diffuser designs employ "smart nozzles" and multi-port systems optimised across broader ambient density profiles. These ensure consistent initial dilution even as seasonal and climate-driven stratification patterns shift, maintaining both environmental and public health protection.

Digital monitoring enables risk-based operations

The era of "black box" outfalls, where operators lack real-time visibility of subsea conditions, is ending. Distributed fibre optic sensing (DFOS) embedded along outfall pipes can detect leaks, strain from ship anchors, and seafloor movement in real time. Autonomous underwater vehicles (AUVs) with sonar and 4K cameras autonomously inspect pipelines for blockages, diffuser failures, and structural degradation – replacing risky, weather-dependent diver inspections.

OPERATIONAL BENEFIT

Digital twins coupled with real-time oceanographic data enable assimilative-capacity-based discharge management. Rather than rigid daily limits, systems can dynamically adjust treatment intensity and discharge rates based on instantaneous water quality and current conditions, optimising energy use while maximising environmental outcomes.

Case study: Hong Kong Harbour Area Treatment Scheme (HATS)

The challenge

Victoria Harbour was choked with raw sewage, causing severe eutrophication, oxygen depletion, and ecosystem collapse. A megacity of 7+ million needed resilient, large-scale sanitation infrastructure without sacrificing marine health.

The solution

HATS Stage 2A constructed a deep tunnel system conveying treated effluent to Stonecutters Island, then discharging through a submarine outfall southwest of Victoria Harbour. Advanced hydraulic modelling optimised diffuser placement to ensure rapid dilution across varying tidal and seasonal conditions.

OUTCOMES

- Dissolved oxygen levels recovered significantly
- *E. coli* and ammonia concentrations fell to acceptable ranges
- Cross-harbour swimming events resumed after decades
- Coral communities reestablished in eastern waters
- Water quality resilience preserved despite 40+ years of population growth.

TRANSFERABLE LESSON

HATS demonstrates that rigorous hydrodynamic engineering, combined with centralised treatment and deep-sea discharge, creates resilient infrastructure capable of supporting megacity sanitation while restoring ocean health – proof that urbanisation and marine ecosystem recovery can coexist when climate and water security drive design decisions.

Practical recommendations

1. INTEGRATE CLIMATE ADAPTATION INTO DESIGN STANDARDS

Embed projected sea-level rise, future storm intensities, and stratification scenarios (RCP 4.5/8.5) into new outfall design criteria. Replace historical-baseline assumptions with forward-looking, adaptive hydraulic profiles that withstand 2050–2100 climate conditions, not just past averages.

2. DEPLOY REAL-TIME MONITORING AND DIGITAL TWINS

Retrofit existing systems and mandate digital integration in new projects: oceanographic buoys, DFOS sensors, and supervisory control and data acquisition (SCADA) linkage feeding digital twins. Enable dynamic discharge management based on assimilative capacity rather than static limits, improving operational resilience and environmental outcomes while reducing energy footprint.

3. FOSTER INTERDISCIPLINARY, MULTI-SECTOR GOVERNANCE

Outfall decisions must unite engineers, oceanographers, public health officials, environmental regulators, and coastal communities. Integrate water security, pathogen control (including antimicrobial resistance dynamics), and ecosystem recovery into a unified framework that respects local ocean-use priorities (aquaculture, recreation, desalination intakes).

Conclusions

Marine outfall systems are no longer invisible endpoints of the urban water cycle. They are frontline infrastructure for coastal resilience, linking SDG 6 (Clean Water and Sanitation) to SDG 14 (Life Below Water). Investment in climate-adapted design, digital monitoring, and collaborative governance is both an engineering imperative and a moral responsibility—ensuring that billions of coastal residents enjoy secure water and thriving marine ecosystems.

| 1.6 |

Nature-based solutions in urban drainage

Authors: *Peter M. Bach, Veljko Prodanovic, Sylvie Spraakman, Luis Sañudo-Fontaneda, Manfred Kleidorfer on behalf of the Joint Committee on Urban Drainage (JCUD) Specialist Group*

Introduction

Urban drainage is being asked to do more than ever before. Cities face intensifying rainfall and pluvial flooding, longer and more frequent droughts that strain water supplies, persistent water quality challenges from emerging contaminants, and a growing need to deliver cooling, biodiversity and amenity in ever-densifying urban environments. Conventional grey infrastructure was not designed for this, and costly retrofits to existing systems will not deliver what is needed. Urban nature-based solutions (NBS) have emerged as a central response, and over the past three years, they have moved decisively from experimental pilots to gradual mainstream practice in many cities worldwide, complementing or even replacing grey infrastructure.

This contribution to the Global Trend Report focuses specifically on advances in NBS for urban drainage and stormwater management, where water is both the medium of intervention and the principal driver of multiple co-benefits. Whilst NBS should not and cannot be viewed solely in a single, isolated discipline, we focus on it as a distributed asset, integrated with existing drainage infrastructure. NBS in urban drainage is, first and foremost, a climate-resilience and water-security strategy, addressing flood risk, drought adaptation, water quality compliance and combined sewer overflow (CSO) mitigation.

Here, we outline several key trends and emerging knowledge gaps that have been prevalent in the urban NBS research and practice over the past few years. These will continue to evolve into the future as more knowledge becomes available. The five key trends define the current state of the field are:

1. A clear shift from one-size-fits-all designs towards context sensitive, climate-tailored solutions, more integrated water management and urban regeneration.
2. Multi-functionality has moved from being a co-benefit to a core design goal. Water acts as the main driver for heat mitigation, biodiversity, and amenity improvement.
3. Performance evaluation is converging slowly on a common set of metrics, even though quantification methods and uncertainty handling remain inconsistent.
4. Digitalisation, low-cost IoT sensors, real-time control and AI-powered solutions are starting to address the field's biggest historical weakness: lack of long-term performance.
5. Investment is growing, but remains below climate adaptation needs, while equity, green gentrification and asset management standards remain the unsolved frontier.

Key terminology

Urban nature-based solutions (NBS) are nature-inspired actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges effectively and adaptively, while providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). They are also frequently known worldwide by other terms including blue-green infrastructures (BGI), water sensitive urban design (WSUD), sustainable drainage systems (SuDS), sponge cities, stormwater control measures (SCMs) or low impact development (LID), among other terms (Fletcher et al., 2015; Probst et al., 2022). They encompass interconnected green and blue spaces in the form of infrastructure (e.g. bioretention, wetlands, green roofs) or active management (e.g. irrigation) of existing urban nature. These systems are not only capable of managing water, but are also multi-functional, i.e. a single NBS asset has the capacity to deliver several services concurrently, referred to collectively as 'ecosystem services' (e.g. flood reduction, evaporative cooling, habitat, and amenity). NBS have been widely recognised as a key element in helping cities adapt to climate change impacts and to reduce the impact of rapid urbanisation, all while safeguarding quality of life of cities.

With rapid digitalisation of our water systems, we are also seeing concepts like **real-time control (RTC)** enter the NBS space, allowing active operation of stormwater assets using sensors and predictive models to optimise performance dynamically. The future trend appears to be moving towards the development of **digital twins**, a live digital representation of the physical system, fed by sensor data and model outputs to support operational decisions.

Several further concepts used throughout this contribution warrant clarification. **Combined sewer overflow (CSO)** refers to discharge from a combined sewer to a receiving waterbody when system capacity is exceeded, and CSO mitigation has emerged as a central climate-resilience target for urban drainage NBS. **Non-stationarity** describes the condition in which the statistical properties of climate variables change over time, invalidating the assumption that historical rainfall records describe future risk. This concept now directly shapes NBS design-rainfall standards.

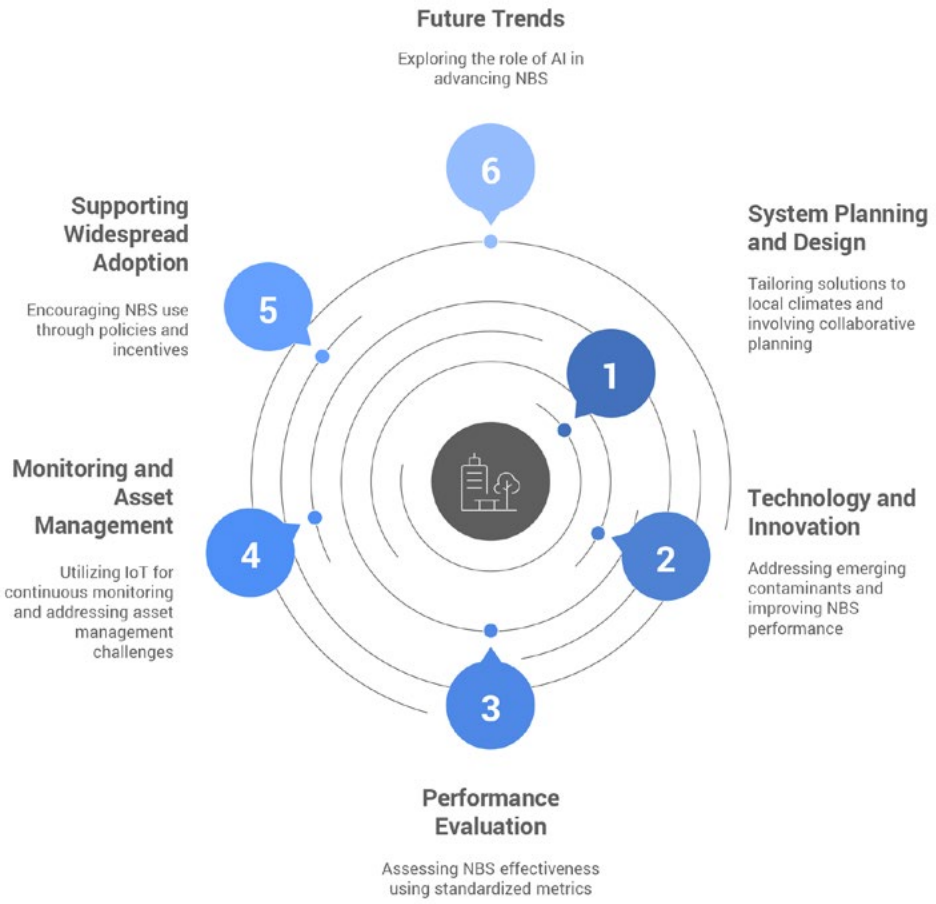


Figure 1.7. Summary of key advancements in NBS in urban drainage that define the major trends

Key insights

There have been major advancements in urban NBS from an urban drainage perspective (summarised in Figure 1.7), specifically in the areas of system design, implementation, monitoring, asset management, performance quantification, and policies guiding their adoption worldwide, both in the Global North and South. It has become clear that water plays a key role for urban NBS to deliver other ecosystem services and conscious planning and design focused around water management remains a key element of many urban NBS projects. Across these advances, a tension emerges that frames the rest of this contribution: technical capability is rapidly outpacing the institutional, financial, and equity frameworks needed to deploy NBS at scale and to make their climate-resilience claims defensible.

System planning and design

For climate resilience, the most consequential design shift is the move from historical norms to forward-looking, context-tailored solutions that anticipate the climate conditions cities will actually face. A clear shift is evident away from a 'one-size-fits-all' mindset when it comes to urban NBS (Ghaderian et al., 2025; van der Meulen, 2024). Context-sensitive awareness has increased through a greater number of publications that deal with systematic implementation of urban NBS (Han et al., 2025). These are conscious efforts to not only design solutions tailored to the local and future climate shifts (e.g. feasibility in arid climates, see Bogis et al., 2021), but also to better involve collaborative planning, co-design, and decision-making (e.g. in Australia, see Naserisafavi et al., 2022), which is particularly valuable in the Global South (e.g. in Brazil and Costa Rica, refer to Lemes de Oliveira et al., 2025; Pérez Rubi and Hack, 2021). In addition to context-sensitive design, multi-functionality has also become a key driver for supporting NBS design (Alves et al., 2024; Eckert, 2025) as water's role in delivering further performance for services like heat mitigation and biodiversity has become clear from literature across domains. The benefits of restoring natural hydrological cycles and retaining soil moisture has been especially important for enhancing heat mitigation (Gobatti et al., 2025), particularly in conditions of concurrent drought and heat waves (Back et al., 2025). Multi-functional thinking is actively seen on-the-ground in case studies like Copenhagen's 'Cloudburst Management Plan', Medellín's 'Corredores Verdes' or Barcelona's 'Superblocks'.

At the technology level, research has been focusing on addressing an increasing array of emerging contaminants, such as pharmaceuticals, microplastics, and per- and polyfluoroalkyl substances (PFAS) (Su et al., 2024), particularly in bioretention systems (Rodgers et al., 2023; Zhang et al., 2025) and treatment wetlands, which also promote circularity through resource recovery (Mancuso et al., 2023). With increasingly stringent regulations such as the revised EU Wastewater Treatment Directive (EU, 2024a) and legally binding targets for nature restoration in the EU through the recent EU Nature Restoration Law (EU, 2024b), current designs of NBS need to advance in performance if these targets are to be met and their widespread adoption is to remain viable. Other design aspects also include improving NBS performance under extreme climate conditions including droughts, floods, and extremely cold and hot climates (Fappiano et al., 2025; Ruangpan et al., 2020) and how they interact with existing centralised water infrastructure, in particular, CSO mitigation (Joshi et al., 2021; Moghanlo and Raimondi, 2024). These themes are targeting specific design elements such as vegetation selection (e.g. drought tolerant, native species) in line with local climate and biome characteristics, resulting in more context-specific solutions.

System performance evaluation

Credible climate-resilience and water-security claims rest on credible measurement, yet quantification methods for urban NBS remain a moving target. With increasing multi-functional planning and design, standardised performance metrics are slowly crystallising, although their exact quantification still lacks consistency. Common approaches assess urban NBS performance against hydrological (peak flow, runoff reduction, infiltration), biodiversity (species richness, habitat connectivity), climate resilience (heat reduction, flood risk, drought resilience), social (recreation, health, perception), and economic (cost–benefit, avoided damages, property value) indicators. Tools and methods are available in research and practice, but are used situationally and with varying levels of uncertainty dependent on data availability and quality.

Modelling tools to quantify the performance and support the planning of urban NBS have, in part, advanced our understanding. The US EPA's Stormwater Management Model (SWMM) remains the dominant software package used in urban drainage research, with many developments complementing it with new modules to better quantify processes like evaporation (Hörnschemeyer et al., 2021) or flood performance (Wu et al., 2025). Industry standards like MIKE URBAN (DHI), PCSWMM (CHI), and InfoWorksICM (Autodesk) have substantially advanced in simulating individual NBS components. At the planning level, support-tools like INVEST, BGIS, UrbanBEATS, SSANTO, and SUSTAIN have steadily updated to consider ecosystem services and trade-offs beyond solely stormwater. Spatial tools are loosely grouped into three dominant categories of identifying location, identifying suitable technologies, and assessing performance. Solving the spatial allocation problem and technology choice has most commonly been achieved with optimisation methods, the most popular one being genetic algorithms (Ruangpan et al., 2020) or multi-criteria decision analysis (Bousquet et al., 2023).

Monitoring and asset management

Perhaps the biggest drawback to widespread urban NBS adoption has been its long-term performance and resilience to shifts in climate. Substantial effort has been invested into refining and quantifying systems through the planning and design process compared to post-implementation. Major advancements in internet of things (IoT) and digitalisation in the last few years has now reduced the cost and implementation effort, enabling continuous NBS monitoring and collection of long-term performance data. Post-implementation monitoring and real-time control approaches to bioretention systems has been an active field of research for the past few years (Spraakman et al., 2020; Zhang et al., 2024). Low cost sensor development for NBS monitoring has also gained viability (Ding et al., 2025), while high-resolution remote techniques are arising as an opportunity for future BGI monitoring (Allende-Prieto et al., 2023). On the ground, we can observe several real-world initiatives of large-scale monitoring networks (e.g. as part of Copenhagen's Cloudburst Management Plan), living laboratories (e.g. Philadelphia's Green Infrastructure Living Laboratory) and digital twin systems starting to emerge. Although long-term performance data of urban NBS systems (beyond 5–10 years) is still scarce (Ghaderian et al., 2025), efforts to monitor are more active than in the previous decade.

Asset management of urban NBS still remains a challenge. Whilst some level of standardisation has been proposed (Langeveld et al., 2022) and solutions are being developed for asset inventories and database (notably in the USA and Norway), progress remains slow and is either based on domain and local knowledge in the municipalities or only carried out minimally to maintain vegetation health. Some "low maintenance" NBS solutions have been proposed such as "Zero-Additional Maintenance WSUD" in Australia (Prodanovic et al., 2022), however, this area is expected to rapidly advance with the increasing potential of real-time monitoring and control, enhanced by artificial intelligence.

Beyond physical asset management, the rapid emergence of generative artificial intelligence (GenAI) since the launch of ChatGPT in late 2022 is reshaping how the NBS community generates and shares knowledge across many industries, with attendant uncertainty about the long-term future of our practice. GenAI tools have, however, evolved to become powerful assistants in bridging knowledge across different domains and have the potential to accelerate how we do things in our respective fields. This is no different for urban NBS and a variety of opportunities for GenAI to support advancements in urban NBS exist (Prodanovic et al., 2024). However, AI-powered practices it still require human agency in scrutinising and improving the information delivered by many AI tools such as large-language models or image generation models so that outputs are communicated with accuracy and transparency. Similar is true for other surrogate AI-based models currently explored for NBS performance evaluation and real-time monitoring (e.g. Zhang et al., 2026), as the explainability and human trust in the results is crucial.

Supporting widespread adoption

Scaling NBS as climate-adaptation infrastructure depends on policy, finance, and knowledge ecosystems that extend well beyond the water sector itself. The NBS concept has been widely embraced within, but also beyond the water sector, especially in the nature conservation, urban planning, and architecture spaces. Acknowledgement of multi-functionality across the domains means that support for widespread adoption comes from multiple stakeholders. National programmes and policies have emerged globally in the past few years to drive innovation and uptake, notable examples including the Spanish, Colombian, and UK SUDSNets, UK Biodiversity Net Gain Policy, Switzerland's Sponge Cities Network, and France's Integrated Stormwater Management Action Plan.

Global investment into NBS (both urban and non-urban) has doubled to $49 billion (Smith et al., 2025), supported by public and private investment or so-called "blended finance" (Gómez et al., 2023), but are still below climate adaptation needs. China's Sponge Cities Program remains the largest investment to date, with over $26 billion in 2023 to support more than 30 cities across the country. Many others, such as Copenhagen, Singapore, cities across Spain and Italy, Medellín, Kigali, and Zurich, have actively embraced a "nature-first" approach to urban planning and development and are leading examples of the major trends in urban NBS. New financial instruments and incentives, such as the introduction of green bonds, nature credits and frameworks like Payment of Ecosystem Services (Tacconi, 2012) or the Taskforce on Nature-related Financial Disclosures (TNFD, 2023) are supporting scaling of urban NBS and creating greater transparency on why the benefits of NBS adoption outweighs its cost, especially in comparison to traditional expansion of existing centralised water infrastructure. Such initiatives as well as the EU Nature Credits, Latin America's Water Funds model, and the Kunming-Montreal Global Biodiversity Framework are all efforts towards incentivising NBS use in cities for economic and political reasons.

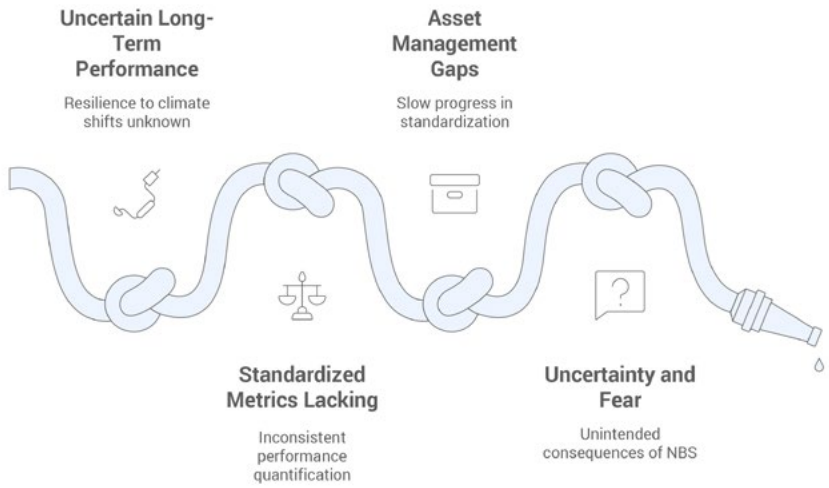


Figure 1.8. Key challenges in scaling NBS and future research needs

Although prevalent in the Global South, many cities in the Global North are also seeking ways to "leapfrog" (Hsu et al., 2020) to NBS or a 'green-first' mindset, seen in the example of Philadelphia's living laboratory. Knowledge networks can further support this widespread adoption and are active internationally, particularly within IWA with the recent establishment of the NBS Cluster and the rebirth of the International Blue-Green Infrastructures working group within the JCUD Specialist Group. Perhaps the greatest challenge to adoption in practice is still the uncertainties around NBS incorporation in urban landscapes to cope with rapid urban development. In that vein, there is a gap in how communities and practitioners perceive and co-create knowledge around NBS, representing a barrier for implementation (Sañudo-Fontaneda and Robina-Ramírez, 2019). Effective approaches and examples have been identified for diverse urban typologies, most notably also the approaches adopted in Kigali, Rwanda for informal settlements using a system of micro-interventions. Nevertheless, fear and uncertainty over unintended consequences of widespread NBS implementation, in particular questions of equity and green gentrification are still prevalent (Rigolon and Németh, 2020) and require deeper knowledge.

Case study: Copenhagen's Cloudburst Management Plan

Copenhagen offers the longest-running and most thoroughly evaluated example of NBS-led urban drainage transformation explicitly framed around climate resilience. On 2 July 2011 the city was hit by a 1,000-year cloudburst event that delivered roughly 150 mm of rain in two hours and caused damages of close to EUR 1 billion, much of it from contaminated floodwater entering buildings via a combined sewer system unable to cope with the loading. The 2010 and 2014 cloudbursts that bracketed it confirmed that the events were not freak occurrences. The City of Copenhagen adopted the Cloudburst Management Plan in 2012 as part of a wider Climate Adaptation Plan (The City of Copenhagen, 2012).

Approach

The plan rejected reliance on additional underground sewer capacity in favour of a hybrid grey-blue-green strategy. Around 300 surface projects across the city centre and priority catchments were programmed, including streets engineered to convey water during extreme events, blue-green corridors along major rights-of-way, distributed retention in parks and squares, and selective separation of stormwater from foul flows. Design rainfall was scaled to a 100-year event under 2100 climate projections, accommodating a projected 30-50% increase in extreme rainfall intensity.

Outcomes

The city's socio-economic cost-benefit analysis showed that a combined grey-blue-green solution generated approximately 50% greater net societal savings than expanding the conventional sewer network alone, even before accounting for qualitative co-benefits including biodiversity, amenity and health. The Greater Copenhagen Utility (HOFOR) was the operating partner, and the plan was financed through a combined model of water-tariff revenue, taxes and private contributions, enabled by a national legislative reform that Copenhagen successfully advocated. Large-scale post-implementation monitoring is increasingly feeding back into operations.

Challenges

Implementation has not been frictionless. The original 20-year horizon has come under cost and timeline pressure as inflation and labour shortages have affected delivery. Long-term performance data on surface assets is still accumulating, and questions remain about how the system will perform under future compound hazards such as concurrent drought, heat and flood.

Transferable lessons

Three lessons stand out. Firstly, framing the plan as urban improvement rather than as engineering investment unlocked political and public support. Secondly, integrating utility, planning, transport, parks and finance functions through a shared Cloudburst Formula was decisive in implementation. Finally, early national level legislative reform was a prerequisite for the financing model and could not be retrofitted later.

Other leading examples

Other leading examples mentioned throughout the discussion are summarised in Table 1.1 below.

Table 1.1 Further examples of NBS programmes and initiatives around the world, their key drivers, outcomes and lessons

Programme	Key driver(s)	Approach	Notable outcome	Transferable lesson
Singapore's ABC Waters	Limited freshwater, flood, heat	Naturalising drains, multi-functional BGI, reservoir reuse	Bishan-Ang Mo Kio Park, integrated park-river restoration with measurable biodiversity gains	Combine flood, supply and amenity goals early in project
Medellin Corredores Verdes	Urban heat, biodiversity loss	Network of green corridors and tree planting	Local temperature reductions of up to 4°C reported in corridor segments	Distributional equity through targeted neighbourhood selection
China's Sponge Cities	Pluvial flooding, rapid urbanisation	Hybrid green-grey at city scale across 30 sites	Mixed: substantial investment but persistent flood risk in some pilots	Local model calibration is critical; foreign blueprints fail without adaptation
Philadelphia Green City, Clean Waters	CSO compliance	25-year living lab model with long-term performance monitoring	CSO reductions evidenced; ~USD 2.4 bn programme	Federal consent decrees can be a powerful lever to mainstream NBS
Kigali (informal settlements)	Hillside flood and landslide risk, equity	Micro-interventions integrated with settlement upgrades	Improved local resilience without displacement of residents	Co-design with informal-settlement residents is a prerequisite, not an add-on

Recommendations

Different priorities and recommendations can be made for different audiences.

- **For utilities:** Integrate NBS asset registers with conventional sewer asset data and invest in low-cost monitoring networks early. Treat NBS as a portfolio of distributed assets requiring proactive, not reactive, maintenance. Use real-time control on priority assets where water-quality compliance or CSO reduction is at stake. Consider AI integration early in the process.
- **For policymakers and regulators.** Mandate or incentivise NBS in updated urban-water and climate-adaptation regulation, and provide enabling legislation for blended finance. Embed NBS into building, planning, and stormwater codes rather than relying on voluntary adoption. Retrofitting after the fact is more difficult and expensive.
- **For researchers.** Focus on three under-addressed areas: (1) long-term post-construction performance under climate non-stationarity (beyond 10 years); (2) standardised, transferable methods for quantifying multi-functional benefits and their uncertainty; and (3) equity outcomes of NBS deployment, including green-gentrification mitigation strategies. Additionally, looking forward, consider explainable AI and human-in-the-loop GenAI research directions.
- **For funders and investors.** Act on the strengthening evidence base for NBS economic value: avoided flood damages, lower whole-of-life cost relative to grey alternatives, and biodiversity and water-quality co-benefits. Push for standardised metrics that allow comparable due diligence across cities.

- **For practitioners.** Adopt context-sensitive design as the baseline. Select vegetation and configurations matched to local climate trajectories rather than to historical norms. Design for multi-functionality from the outset. Build co-design with communities into project initiation.
- **For knowledge networks.** IWA's NBS Cluster and the JCUD's renewed International Blue-Green Infrastructures (iBGI) working group are well-positioned to translate research advances into accessible practitioner guidance and to bridge the persistent Global North to Global South gap in implementation knowledge.

Conclusion and outlook

NBS in urban drainage have moved from the margins to the mainstream of climate-resilient water management over the past few years. Investment is growing, design is becoming context-sensitive and multi-functional, and a digital-monitoring revolution is starting to address the long-standing weakness of post-construction evidence. Connections to the broader climate-resilience and water-security agenda are now explicit in leading frameworks, from the EU Nature Restoration Law to the TNFD.

The field is not yet where it needs to be. Although substantial investments have been made to drive uptake of urban NBS, predictions warn that urban NBS are still woefully underfinanced if climate adaptation targets are to be reached (UNEP, 2025). Long-term performance under compound climate hazards is poorly characterised. Asset management standardisation lags grey infrastructure by decades. Persistent equity concerns risk undermining public acceptance if not addressed directly. The next phase of work will be defined less by demonstrating that NBS practices work and more by ensuring they are deployed at scale, equitably, in ways that hold up under the climate conditions cities will actually face. With advancements in digitalisation and AI, proactive policies that enact pressure on cities, and greater interdisciplinary collaboration, we are heading in the right direction.

References

Allende-Prieto, C., Roces-García, J., Recondo, C., Sañudo-Fontaneda, L., and González-Moradas, M. d. R. (2023). An exploratory methodology based on high resolution remote sensing techniques for soil moisture determination with prospective applications in vegetative SuDS. *Urban Water Journal*, 20(8), 1006–1020.

Alves, A., van Opstal, C., Keijzer, N., Sutton, N., and Chen, W.-S. (2024). Planning the multifunctionality of nature-based solutions in urban spaces. *Cities*, 146, 104751.

Back, Y., Jasper-Tönnies, A., Bach, P. M., Kumar, P., Santamouris, M., Rauch, W., and Kleidorfer, M. (2025). Current interventions are inadequate to maintain cities' resilience during concurrent drought and excessive heat. *Earth's Future*, 13(4), e2024EF005208.

Bogis, A., Bork, D., and Miller, P. (2021). Are green infrastructure strategies suitable in arid climates? A design feasibility study from Jeddah City, Saudi Arabia. *International Journal of Architecture and Planning*, 1(1), 9–18.

Bousquet, M., Kuller, M., Lacroix, S., and Vanrolleghem, P. A. (2023). A critical review of multicriteria decision analysis practices in planning of urban green spaces and nature-based solutions. *Blue-Green Systems*, 5(2), 200–219.

Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (2016). Nature-based solutions to address global societal challenges. IUCN: Gland, Switzerland.

Ding, N., Zhu, Q., Cherqui, F., Walcker, N., Bertrand-Krajewski, J.-L., and Hamel, P. (2025). Laboratory performance assessment of low-cost water level sensor for field monitoring in the tropics. *Water Research X*, 27, 100298.

Eckert, K. H. (2025). Multifunctionality of Nature-based solutions a scoping review of strategic planning processes. *Discover Sustainability*, 6(1), 907.

EU. (2024a). *Directive (EU) 2024/3019 on the European Parliament and of the council concerning urban wastewater treatment*. https://eur-lex.europa.eu/eli/dir/2024/3019/oj

EU. (2024b). *Regulation (EU) 2024/1991 of the European Parliament and of the council on nature restoration and amending Regulation (EU) 2022/869*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991&qid=1722240349976

Fappiano, F., Maurer, M., and Leitão, J. P. (2025). Blue-Green Infrastructure for pluvial flood risk reduction in rapidly urbanizing peri-urban areas: Strategic planning for uncertain futures. *Journal of Environmental Management*, 395, 127843.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., and Bertrand-Krajewski, J.-L. (2015). SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525–542.

Ghaderian, M., Hakimian, P., and Shahab, S. (2025). The trajectory of water sensitive urban design: integrating water management with urban planning and design. *Australian Planner*, 61(1), 29–42.

Gobatti, L., Bach, P., Maurer, M., and Leitão, J. (2025). Impact of soil moisture content on urban tree evaporative cooling and human thermal comfort. npj *Urban Sustainability*, 5(1), 26.

Gómez, S., Purata, V. L. P., and E., R. S. (2023). *Pathways to Unblocking Private Financing for Nature-based Solutions*. https://www.wri.org/update/pathways-unblocking-private-financing-nature-based-solutions

Han, D., Xia, J., and Wu, D. (2025). Ecological resilience and urban health: A global analysis of research hotspots and trends in nature-based solutions. *Forests*, 16(8), 1305.

Hörnschemeyer, B., Henrichs, M., and Uhl, M. (2021). SWMM-UrbanEVA: A model for the evapotranspiration of urban vegetation. *Water*, 13(2), 243.

Hsu, D., Lim, T. C., and Meng, T. (2020). Rocky steps towards adaptive management and adaptive governance in implementing green infrastructure at urban scale in Philadelphia. *Urban Forestry & Urban Greening*, 55, 126791.

Joshi, P., Leitão, J. P., Maurer, M., and Bach, P. M. (2021). Not all SuDS are created equal: Impact of different approaches on combined sewer overflows. *Water Research*, 191, 116780.

Langeveld, J. G., Cherqui, F., Tscheikner-Gratl, F., Muthanna, T. M., Juarez, M. F.-D., Leitão, J. P., Roghani, B., Kerres, K., do Céu Almeida, M., and Werey, C. (2022). Asset management for blue-green infrastructures: a scoping review. *Blue-Green Systems*, 4(2), 272–290.

Lemes de Oliveira, F., Bezerra, M. d. C. d. L., Nunes, O. V. R., Duarte, E. D. A. A., Castaldo, A. G., and Almeida, D. N. d. (2025). Nature-based solutions for stormwater management: Co-creating a multiscalar proposal in the Global South. *Land*, 14(4), 740.

Mancuso, G., Lavrnić, S., Canet-Martí, A., Zaheer, A., Avolio, F., Langergraber, G., and Toscano, A. (2023). Performance of lagoon and constructed wetland systems for tertiary wastewater treatment and potential of reclaimed water in agricultural irrigation. *Journal of Environmental Management*, 348, 119278.

Moghanlo, S. J., and Raimondi, A. (2024). Impacts of blue-green infrastructures on combined sewer overflows. *Nature-Based Solutions*, 100208.

Naserisafavi, N., Coyne, T., Melo Zurita, M. d. L., Zhang, K., and Prodanovic, V. (2022). Community values on governing urban water nature-based solutions in Sydney, Australia. *Journal of Environmental Management*, 322, 116063. https://doi.org/https://doi.org/10.1016/j.jenvman.2022.116063

Pérez Rubi, M., and Hack, J. (2021). Co-design of experimental nature-based solutions for decentralized dry-weather runoff treatment retrofitted in a densely urbanized area in Central America. *Ambio*, 50(8), 1498-1513.

Probst, N., Bach, P. M., Cook, L. M., Maurer, M., and Leitão, J. P. (2022). Blue Green Systems for urban heat mitigation: mechanisms, effectiveness and research directions. *Blue-Green Systems*, 4(2), 348-376.

Prodanovic, V., Bach, P. M., and Stojkovic, M. (2024). Urban nature-based solutions planning for biodiversity outcomes: Human, ecological, and artificial intelligence perspectives. *Urban Ecosystems*, 27(5), 1795-1806.

Prodanovic, V., Hatt, B., Fowdar, H., Al-Ameri, M., and Deletic, A. (2022). Zero additional maintenance stormwater biofilters: from laboratory testing to field implementation. *Blue-Green Systems*, 4(2), 291-309. https://doi.org/https://doi.org/10.2166/bgs.2022.030

Rigolon, A., and Németh, J. (2020). Green gentrification or 'just green enough': Do park location, size and function affect whether a place gentrifies or not? *Urban Studies*, 57(2), 402-420.

Rodgers, T. F., Wang, Y., Humes, C., Jeronimo, M., Johannessen, C., Spraakman, S., Giang, A., and Scholes, R. C. (2023). Bioretention cells provide a 10-fold reduction in 6PPD-quinone mass loadings to receiving waters: evidence from a field experiment and modeling. *Environmental Science & Technology Letters*, 10(7), 582-588.

Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L. S., Capobianco, V., Oen, A. M., McClain, M. E., and Lopez-Gunn, E. (2020). Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. *Natural Hazards and Earth System Sciences*, 20(1), 243-270.

Sañudo-Fontaneda, L., and Robina-Ramírez, R. (2019). Bringing community perceptions into sustainable urban drainage systems: The experience of Extremadura, Spain. *Land Use Policy*, 89, 104251.

Smith, M., Gammie, G., Song, J., Atwell, B., Shemie, D., Bennett, M., Adriazola, J. C., Joubert, I. J., and Tanguy, P. (2025). *Doubling Down on Nature: State of Investment in Nature-based Solutions for Water Security*. Forest Trends & The Nature Conservancy.

Spraakman, S., Van Seters, T., Drake, J., and Passeport, E. (2020). How has it changed? A comparative field evaluation of bioretention infiltration and treatment performance post-construction and at maturity. *Ecological Engineering*, 158, 106036.

Su, J., Wang, M., Zhang, D., Sun, C., Zhao, X., and Razi, M. A. B. M. (2024). A systematic and bibliometric review of bioretention system (BRS) for urban ecosystem regulation services. *Urban Climate*, 55, 101923.

Tacconi, L. (2012). Redefining payments for environmental services. *Ecological economics*, 73, 29-36.

The City of Copenhagen. (2012). *The City of Copenhagen Cloudburst Management Plan 2012*. https://international.kk.dk/sites/default/files/2021-09/Cloudburst%20Management%20plan%202010.pdf

TNFD. (2023). *Getting started with adoption of the TNFD recommendations*. https://tnfd.global/recommendations/getting-started-with-tnfd/

UNEP. (2025). *State of Finance for Nature in Cities 2024: From Grey to Green, Better data to finance nature in cities*.

van der Meulen, G. J. (2024). Enhancing context specificity of Water-Sensitive Urban Design: An urban design perspective on Indian secondary cities.

Wu, W., Jamali, B., Marshall, L., Deletic, A., and Zhang, K. (2025). A Water Sensitive Urban Design (WSUD) Planning Framework for Catchment-Scale Urban Pluvial Flood Mitigation Targets. *Water Research*, 124095.

Zhang, J., Prodanovic, V., O'Carroll, D. M., & Zhang, K. (2026). Using surrogates to predict trace organic contaminant removal in stormwater biofilters. *Water Research*, 126360.

Zhang, J., Prodanovic, V., O'Carroll, D. M., Zheng, Z., and Zhang, K. (2024). Real time control of stormwater biofilters improves the removal of organic chemicals. *Water Research*, 266, 122411.

Zhang, K., Yuan, L., Deletic, A., and Prodanovic, V. (2025). Fate of wastewater trace organic chemicals in vegetated biofiltration systems. *Water Research*, 273, 122953.

| 1.7 |

Leading issues in efficient urban water management: linking climate resilience, digital resilience and water security

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Introduction

This contribution aims to offer insights from the IWA Efficient 2025 Conference, held in Melbourne. Efficient urban water management has never been more critical. Cities around the world are working together to respond to pressures from climate change, rapid urbanisation, and expectations for sustainability. Together, these pressures are increasing stress on water systems, exposing vulnerabilities related to droughts, floods, water scarcity, and water quality pressures, while raising concerns about system reliability.

Addressing these challenges requires collaboration across sectors and borders. Efficiency is no longer only about reducing water consumption; it is also about building resilience, maintaining trust, and helping cities remain liveable under changing climatic and economic conditions. In this sense, efficient urban water management is closely linked to water security: the ability of societies to secure sufficient, safe, reliable, and affordable water services under changing conditions.

Traditionally, water efficiency has been viewed mainly as a means to reduce consumption. Today, however, it is increasingly recognised as a broader concept – one that not only manages demand but also contributes directly to climate resilience and mitigation. By lowering energy requirements across the water cycle and reducing greenhouse gas emissions, efficiency delivers benefits that reach well beyond the water sector. At the same time, effective efficiency depends on good governance – balancing competing interests, ensuring fairness, and creating the financial and institutional conditions that allow innovation to take root.

As well as drawing on the IWA Efficient 2025 Conference, this chapter highlights case studies from diverse regions and contexts.[1] It highlights climate resilience and digital resilience as two significant and interlinked issues in efficient urban water management today. Efficiency should be understood not only as an adaptation measure, but also as a form of mitigation – contributing to energy savings, emissions reduction, and system reliability. It can also help strengthen water security, particularly in cities facing drought, flooding, infrastructure stress, or growing uncertainty in demand and supply.

This chapter contributes to the IWA Global Trends and Challenges in Water Science, Research and Management Compendium, aligning with cross-cutting themes under SDG 6, SDG 13, and SDG 17. Its central message is that efficient urban water management can support water security when it is framed not only as a technical efficiency agenda, but also as a climate-resilience, digital-resilience, and governance agenda.

Key terminology

- **Climate resilience:** The ability of urban water systems to cope with droughts, floods, and extreme weather, while adapting to long-term climate changes.
- **Digital resilience:** The capacity to use and protect digital tools – such as AI, smart meters, and data platforms – while managing risks from data gaps, privacy issues, and cyber threats.
- **Governance:** The rules, policies, and institutions that guide water management, ensuring fairness, accountability, and support for innovation.
- **Data governance:** The standards and practices for collecting, sharing, and protecting water data to support reliable, ethical, and secure decision-making.
- **Water security:** The ability of societies to secure sufficient, safe, reliable, and affordable water services under changing conditions.
- **Circular water management:** An approach that promotes the reuse, recycling, and diversified use of water sources – such as rainwater, stormwater, and wastewater – to reduce pressure on conventional supplies and improve resilience.

[1] Numbers in parentheses throughout this paper refer to abstract numbers from the IWA Efficient 2025 Conference, Melbourne

Key insights

Across the IWA Efficient 2025 Conference, several cross-cutting insights emerged on how efficiency is being used to support climate resilience, digital resilience, governance, and water security. Together, these insights suggest that efficiency is increasingly understood not only as a technical goal, but also as a practical way to manage uncertainty, reduce risk, and support more resilient and inclusive urban water services.

- Efficiency is increasingly linked to climate strategy. Saving water can also mean saving energy and reducing greenhouse gas emissions. At the same time, efficiency can help cities manage scarcity, reduce stress on supply systems, and improve reliability during climate-related shocks.
- Circular and locally adapted approaches, such as rainwater harvesting, stormwater reuse, and wastewater recycling, can strengthen resilience. Cities are moving toward flexible, integrated systems that reuse water at multiple scales. These approaches can reduce dependence on single supply sources, although their success depends on appropriate design, maintenance, regulation, and public acceptance.
- Digital tools can improve efficiency, but they also introduce new vulnerabilities. The expansion of smart meters, AI forecasting, and internet of things (IoT) systems transforms utility management by enabling more timely and targeted decisions. However, such systems also depend on reliable data, institutional capacity, cybersecurity safeguards, and trust among utilities, regulators, technology providers, and customers.
- Governance helps enable long-term impact. Regulatory models are shifting toward learning-based and adaptive approaches that support collaboration rather than strict compliance alone. Governance determines whether efficiency measures are financially viable, socially legitimate, and adaptable to changing climate and service conditions.
- Data should be treated as both a shared resource and a public-interest responsibility. Shared, interoperable systems can build trust and transparency. However, data sharing must be supported by clear standards for quality, privacy, accountability, and cybersecurity. Without these safeguards, digital innovation may increase rather than reduce risk.
- Equity and social acceptance are central to effective efficiency. Efficiency measures are more likely to be effective when fairness and participation are considered in policy design. Measures such as pricing reform, alternative water programmes, digital engagement, or demand management may create uneven impacts if vulnerable communities are not taken into consideration.

Case studies

Climate resilience and water security

Water efficiency is increasingly recognised as part of climate resilience, offering cities practical ways to adapt to climate pressures while also contributing to broader climate goals. Efficiency measures can directly reduce energy demand across the water cycle and lower greenhouse gas emissions, creating climate benefits that extend beyond water alone. This dual role was emphasised in research that connected efficiency to climate strategies and quantified its contribution to energy and emissions reductions (No. 141, No. 162).

Several examples show how efficiency can support adaptation in practice. Stormwater harvesting demonstrates how extreme rainfall can be transformed from a hazard into a resource (No. 90). Community-focused initiatives, including alternative water offsets, highlight how resilience planning can also advance equity by ensuring that vulnerable groups share the benefits of new supply options (No. 92). Monitoring systems that improve the performance of rainwater harvesting (No. 28) and large-scale programmes for reusing rainwater, stormwater, and wastewater – such as Melbourne's circular water city approach (No. 94) – illustrate how diversification strengthens system reliability while reducing dependence on conventional potable sources.

Context matters as well. In Colombia, blue-green infrastructure has been applied to reduce flood and landslide risks in data-limited catchments (No. 158), showing how nature-based solutions can provide resilience even where technical data are scarce. Experiences in Australia underline the importance of balancing efficiency gains with service reliability and customer expectations (No. 47).

These examples show outcomes beyond reduced water consumption, including improved system reliability, greater flexibility in water sourcing, reduced exposure to climate-related risks, and potential energy and emissions benefits. At the same time, the challenges are practical and institutional: cities must ensure that alternative sources are safe, maintained, publicly accepted, and integrated into existing planning and investment frameworks.

KEY INSIGHT

Efficiency can support climate resilience and mitigation when integrated into circular and adaptive approaches. It can also contribute to water security when linked to local climate risks, service-reliability goals, and community needs.

Governance

Case studies across different regions revealed that effective governance blends structure with flexibility. Budget-based frameworks and performance standards can help incentivise innovation, while overly prescriptive rules can limit adaptability. California's first budget-based efficiency regulation (No. 26) demonstrated how measurable targets can drive continuous improvement when accompanied by technical support and transparent data sharing.

At the same time, regulatory approaches are shifting toward learning-based systems that emphasise accountability through results rather than rigid compliance. Coordination and standardisation, such as those seen in the framework for England and Wales for smart water metering (No. 19), have shown that harmonised governance enables scalability while reducing uncertainty for utilities and vendors alike.

Equity is increasingly viewed as a governance issue, not merely a social goal. Programmes that design tariffs and support mechanisms for vulnerable groups – like those discussed in California's regulatory evolution (No. 144) – are gaining traction, ensuring that efficiency measures do not exacerbate inequality. Economic frameworks that recognise the multiple benefits of recycling, reuse, and efficiency—including avoided costs, resilience dividends, and climate co-benefits – are expanding the financial rationale for investment (No. 51).

Governance is not limited to national institutions. City-level governance has also emerged as a testing ground for adaptive management. The integration of smart data management into environmental governance (No. 103) demonstrated how cross-sector coordination – between utilities, regulators, and data providers – can enhance transparency and accountability.

These examples show that efficiency policies depend on clear incentives, coordination, accountability, and investment conditions. Key challenges include aligning institutions, balancing affordability with cost recovery, and keeping regulations flexible enough to respond to changing climate and demand conditions. They also suggest that governance for efficiency should support learning, adaptation, and trust, especially where water-security risks require cooperation among utilities, regulators, communities, and technology providers.

KEY INSIGHT

Adaptive, transparent, and equity-focused governance can help translate climate-resilience and water-security goals into practical utility and policy action.

Digital resilience

Digital transformation is redefining what efficiency means in practice. AI, smart sensors, and advanced analytics are changing how cities monitor, forecast, and manage water use – but they also expose new vulnerabilities. The cases presented at Efficient 2025 show that digital resilience requires more than technology alone. It requires governance, collaboration, and human capacity.

Data-driven forecasting, as demonstrated through next-generation demand models using smart meters, remote sensing, and AI (No. 12), is enhancing predictive accuracy and operational flexibility. Leak detection systems that integrate acoustic analytics and AI algorithms (No. 154) have significantly reduced non-revenue water while allowing utilities to respond faster to infrastructure failures. Similarly, AI-driven conservation platforms that deliver personalised, rule-based recommendations to customers (No. 57) show how digital tools can motivate behavioral change and enhance participation in efficiency programmes.

However, the expansion of digital technologies introduces new vulnerabilities. Data privacy, interoperability, and cybersecurity have become shared concerns across utilities and governments. The ATHENA EU research project (No. 56) illustrates how training and capacity building for cybersecurity are vital to protect digital infrastructure and ensure that technological innovation serves the public good rather than deepening divides.

A recurring theme across these experiences is the need to treat data as both a technical and ethical resource. Shared standards for data governance—covering interoperability, privacy, and cybersecurity – are emerging as prerequisites for trustworthy digital systems. Yet, technology adoption also depends on people: the ability of staff and managers to interpret and apply data insights responsibly.

These digital examples show outcomes such as improved demand forecasting, faster leak detection, more targeted conservation programmes, and better operational awareness. Key challenges include data gaps, uneven digital capacity, cybersecurity exposure, and the risk that technology-driven systems may be difficult for some users or institutions to understand and trust. They also suggest that digital resilience should be planned as part of water security, so that digital systems are not only "smart," but also secure, understandable, interoperable, and supported by skilled people.

KEY INSIGHT

Digital resilience can support climate resilience and water security when technology, governance, and human capacity are developed together.

Recommendations

The following recommendations outline practical implications for utilities, policymakers, regulators, researchers, practitioners, funders, and international networks.

For utilities

- **Integrate water efficiency into climate-risk and water security planning:** Linking efficiency programmes to drought preparedness, flood-risk management, demand forecasting, supply diversification, and long-term asset planning can improve reliability and preparedness.
- **Use digital tools while managing digital risks:** Smart meters, AI, IoT, and analytics can support leak detection, demand forecasting, and customer engagement when accompanied by cybersecurity measures, data-quality standards, and staff training.
- **Build staff capacity to use data responsibly:** Digital transformation depends on staff and managers being able to interpret data, communicate insights, and make informed operational decisions.
- **Design efficiency measures with customers and communities in mind:** Attention to affordability, service reliability, and public acceptance can reduce the risk of uneven impacts, especially for vulnerable groups.

For policymakers and regulators

- **Integrate water efficiency, reuse, and circular water management into climate-adaptation and water-security strategies:** This helps frame efficiency as a tool for reducing climate-related risks and strengthening water-system resilience.
- **Support adaptive, learning-based regulation:** Clear goals and accountability can be combined with flexibility, allowing utilities and cities to adjust approaches as climate risks, technologies, and community needs change.
- **Create stable funding and investment frameworks:** Funding models can recognise the long-term value of efficiency, reuse, digital systems, and resilience measures, including avoided costs, reliability benefits, and wider climate and social co-benefits.
- **Set minimum expectations for data governance:** Standards for interoperability, privacy, cybersecurity, transparency, and responsible data use can support trustworthy digital systems.

For researchers and practitioners

- **Strengthen evidence on the wider value of efficiency:** Research can clarify the links between water savings, energy savings, emissions reduction, reliability, and resilience outcomes.
- **Develop transferable lessons from diverse case studies:** Comparative research can identify what worked, what enabled success, what barriers emerged, and how lessons can be adapted to different institutional and climatic contexts.
- **Communicate technical findings in accessible ways:** Translating evidence into practical guidance can support utilities, regulators, city governments, and community stakeholders.

For funders and international networks

- **Support cross-sector and cross-country learning:** International platforms such as IWA Specialist Groups can help share lessons across regions facing similar climate and water-security pressures but differing in institutional capacity.
- **Prioritise projects that combine technical innovation with governance and equity:** Funding for technologies can be paired with support for institutional, human, and social conditions needed for long-term resilience.
- **Encourage integrated approaches:** Projects are more likely to create value when climate resilience, digital resilience, governance, and water security are addressed together rather than separately.

Conclusion

Efficient urban water management is increasingly linked to climate resilience, digital resilience, and inclusive governance. It can support adaptation and mitigation by reducing demand pressures, improving system reliability, and contributing to energy and emissions savings.

For cities and utilities facing droughts, floods, scarcity, quality pressures, and infrastructure stress, efficiency can also contribute to water security, especially when combined with diversified water sources, adaptive planning, reliable data, and public trust.

Digital tools offer new opportunities for forecasting, leak detection, and customer engagement, but they require attention to data quality, cybersecurity, and human capacity. Governance provides the conditions for these tools and strategies to be applied fairly and effectively.

For urban water management, the next step is to connect climate resilience, digital resilience, and governance more closely with the practical water-security challenges facing cities and utilities.

References

Burton, A. (2025). Coordination and standards for smart water metering in England. (No. 19)

Comer, L. (2025). The role of efficiency, recycling, and reuse in supporting water security and supply resilience: The need for a sound economic framework. (No. 51)

Dickinson, M. A. (2025). Climate change and efficient water use: Connecting the dots. (No. 141)

Erbeznik, M. (2025). Navigating California's most aggressive water regulations. (No. 144)

Kenway, S. (2025). Water efficiency is a huge opportunity for cost-effective, high-impact savings of energy, GHG emissions, and costs. (No. 162)

Lee, B. (2025). Alternative water offsets to support healthy and resilient communities. (No. 92)

Matlock, M. (2025). Breaking new ground: Implementing the first budget-based water use efficiency regulation in California. (No. 26)

Medina, L. (2025). Blue–green infrastructure for flood and landslide risk reduction in data-limited tropical catchments: Huila case study in Colombia. (No. 158)

Morgan, C. (2025). Circular water city: Melbourne's progress and potential for reuse of rainwater, stormwater, and wastewater. (No. 94)

Naserizadeh, S. (2025). A personalised AI-driven water conservation system using dynamic rule-based recommendations. (No. 57)

Nguyen, B. (2025). Development of cybersecurity trainings for water utilities: The ATHENA EU research project. (No. 56)

Nirmalaraja, A. (2025). Turning storms into solutions: Stormwater harvesting for climate adaptation. (No. 90)

Smit, M. (2025). Smart monitoring for rainwater harvesting. (No. 28)

Stewart, R. (2025). Next-generation water demand forecasting using smart meters, remote sensing, and AI. (No. 12)

Wilson, T. (2025). Harnessing smart data management for sustainable water and environmental governance. (No. 103)

Wyatt, A. (2025). Managing urban water demands in Australia. (No. 47)

Zeng, W. (2025). Leak detection in smart water networks with integrated acoustic data analytics and AI. (No. 154)

| 1.8 |

Rainwater for climate resilience: a new paradigm for water security through community-based harvesting and adaptive governance

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Introduction

Climate change is fundamentally reshaping how societies need to manage water. Across the world, prolonged droughts, more intense rainfall, urban flooding, groundwater depletion, and deteriorating water quality are becoming increasingly frequent, often within the same region or even the same year. These pressures expose the limits of water systems built primarily around centralised infrastructure. While centralised systems will continue to play a vital role, they alone cannot provide the flexibility, redundancy, and resilience required under rapidly changing climatic conditions. Water management must therefore become more diversified, decentralised, adaptive, and community-oriented.

Among available water resources, rainwater occupies a unique position. Unlike many conventional sources, rainfall is naturally distributed, renewable, and available where people live. When appropriately harvested and managed, rainwater can simultaneously provide safe drinking water, reduce flood risk, supplement groundwater recharge, lower energy consumption, and strengthen local resilience – few resources contribute so directly to water security, climate adaptation, social equity, and community empowerment at once. This multiplicity of benefits requires a shift in how rainwater is perceived: from stormwater to be drained away, or a merely supplementary source, to a strategic resource for climate resilience.

Recognising this transition, the IWA Specialist Group on Rainwater Harvesting and Management (RWHM SG) has promoted an integrated approach combining scientific research, engineering practice, policy dialogue, education, and international collaboration. Initiatives such as the Rain School Initiative, Community-Based Rainwater for Drinking (CBRD), digital monitoring systems, Rain Justice, and the proposed World Rain Day have recently been consolidated under a global framework, Rain for Resilience (R4R), designed to accelerate community-led rainwater innovation worldwide (Han, 2025).

This chapter presents the collective experience of the RWHM SG and proposes a new paradigm for rainwater harvesting and management. It first defines the key concepts and the paradigm shift now under way, then presents international case studies from Cambodia, Myanmar, India, Tanzania, and Mexico that show how community-based rainwater management contributes to climate resilience under diverse environmental and institutional conditions. Finally, it proposes recommendations for governments, researchers, educators, development partners, and international organisations to accelerate the mainstreaming of rainwater harvesting as an essential component of climate-resilient water governance.

Key concepts and paradigm shift

Rainwater harvesting and management (RWHM) has evolved considerably over the past decades. Traditionally regarded as a supplementary supply option or a local engineering practice, it is now increasingly recognised as an integrated strategy for strengthening climate resilience, water security, and adaptive governance. The RWHM SG has contributed to this transformation through research, policy dialogue, demonstration projects, education, and international collaboration, promoting a holistic approach that combines engineering with governance, education, digital innovation, and community participation. The following key concepts underpin this approach.

Key terminology

Rainwater harvesting and management (RWHM) refers to the collection, storage, treatment, distribution, and sustainable management of rainwater for multiple purposes, including drinking water, domestic use, groundwater recharge, ecosystem protection, and climate adaptation.

Community-based rainwater for drinking (CBRD) promotes decentralised drinking-water systems owned and managed by local communities, ensuring long-term sustainability through local responsibility and participation.

The Rain School Initiative (RSI) integrates rainwater harvesting into school education, transforming schools into centres for climate education, citizen science, and practical water management.

Rain Justice promotes equitable access to rainfall by encouraging supportive policies, community participation, and inclusive governance, so that vulnerable populations can benefit from local rainwater resources.

World Rain Day is proposed as an annual global platform that connects climate education, citizen participation, policy dialogue, and practical local action through rainwater harvesting.

These four initiatives, together with an emerging mountain rehydration movement that restores upland soil moisture through micro-scale rainwater traps, have recently been consolidated under Rain for Resilience (R4R), a global initiative led by Rain for All that brings community-led rainwater innovations together under one framework for scaling and policy advocacy (Han, 2025). Collectively, these concepts represent a transition from conventional infrastructure-centred water management toward a broader paradigm that emphasises resilience, participation, and adaptive governance.

The paradigm shift

Table 1.2 summarises the paradigm shift proposed in this paper. Climate resilience requires more than new infrastructure; it requires new ways of governing water, educating society, sharing knowledge, and engaging communities. The sections that follow examine each element of this transition and how it is being implemented through the work of the RWHM Specialist Group.

Table 1.2 A new paradigm for climate-resilient rainwater harvesting and management

Conventional paradigm	Emerging RWHM paradigm
Centralised water supply	Hybrid centralised–decentralised water systems
Water supply	Water security and climate resilience
Engineering infrastructure	Engineering integrated with governance, education and digital innovation
Water users	Active community partners and citizen scientists
Rain as stormwater	Rain as a strategic water resource
Government responsibility	Shared governance among governments, communities, schools, academia and NGOs
Emergency response	Preparedness, adaptation, and resilience
Individual pilot projects	International knowledge networks and collaborative learning

Key insights

The paradigm presented in Table 1.2 reflects six developments that, taken together, form a connected logic rather than a list of independent observations. Recognising rainwater as a strategic resource creates the case for governance reform; governance becomes durable only when paired with education; education and governance together generate the data and demand that justify investment in digital monitoring; and the combination of resource recognition, governance, and data is what makes Rain Justice and World Rain Daypractical instruments rather than slogans.

Rainwater is becoming a strategic resource for climate resilience

Climate change has fundamentally altered the role of rainwater in water management. Rather than serving only as an emergency or supplementary source, rainwater now contributes simultaneously to safe drinking water, flood mitigation, groundwater recharge, energy conservation, and local climate adaptation – few water resources address several Sustainable Development Goals at once. A recent global modelling study estimates that, with appropriate infrastructure, rainwater harvesting could become the primary source of safe drinking water for between 0.45 and 2.08 billion people who currently lack it, underscoring the scale of the resource that remains underused in mainstream water security planning.

Key message: Rainwater should be recognised as a strategic resource for climate resilience and water security.

Governance is becoming as important as engineering

Technical excellence alone cannot guarantee long-term sustainability. Experience from many countries shows that successful rainwater programmes depend equally on institutional support, community ownership, education, financing, and long-term maintenance. The RWHM SG therefore promotes community-based governance in which governments, schools, researchers, NGOs, and local communities jointly share responsibility for planning, operating, and improving rainwater systems.

Key message: Sustainable rainwater management depends on governance as much as engineering.

Education transforms infrastructure into resilience

Climate-resilient infrastructure requires climate-literate communities. The Rain School Initiative illustrates how schools can become centres of climate education where students monitor rainfall, evaluate water quality, operate rainwater systems, and communicate environmental knowledge to their families and communities – turning rainwater harvesting into a long-term investment in future generations rather than simply a construction project.

Key message: Education transforms rainwater systems into long-term resilience-building platforms.

Digital innovation enables adaptive management

Affordable sensors, artificial intelligence, mobile applications, QR-code reporting, and cloud-based databases now enable real-time monitoring of rainfall, storage volumes, water quality, and system performance, supporting adaptive management and encouraging citizen science and evidence-based decision-making.

Key message: Digital innovation strengthens transparency, participation, and adaptive water governance.

Rain Justice promotes equitable water governance

Climate change disproportionately affects vulnerable communities that often have the least access to safe water. Rain Justice recognises that every community should have equitable opportunities to benefit from rainfall, translating equity from an aspiration into operational criteria – such as siting rules, subsidy eligibility, and participation requirements – that determine who can access decentralised rainwater systems and who remains dependent on more vulnerable centralised supply.

Key message: Rain Justice connects social equity with climate-resilient water governance.

World Rain Day links local action with global cooperation

The RWHM SG proposes World Rain Day (3 September) as an annual international platform for promoting rainwater harvesting, climate education, citizen science, and policy dialogue. The proposed date commemorates 1441, when Korea established the earliest known nationwide institutional system for measuring and recording rainfall as part of state water governance (Han and Rohilla, 2025). By anchoring an annual reporting and accountability rhythm to a fixed date – much as World Water Day and World Meteorological Day already do for broader water and climate governance – it would give governments and utilities a recurring occasion to benchmark decentralised rainwater systems against water security and climate-adaptation targets.

Key message: World Rain Day provides an annual global platform linking education, governance, climate adaptation, and community action.

International experiences: translating the new paradigm into practice

The paradigm described in Table 1.2 is no longer a theoretical concept. Across different regions, rainwater harvesting and management is evolving into practical solutions that strengthen climate resilience through education, community participation, governance, technological innovation, and international collaboration. Although each country has unique environmental and institutional conditions, the following experiences illustrate common principles that can be adapted globally.

Cambodia: schools as centres of climate resilience

The Rain School Initiative demonstrates how rainwater harvesting can become a platform for climate education rather than simply a water supply system. Under a Memorandum of Understanding among the Ministry of Education, Youth and Sport (MoEYS), the Royal Academy of Cambodia (RAC), and Seoul National University, the initiative aims to equip 1,000 primary schools nationwide with rainwater harvesting and filtration systems (Yarrow-Soden, 2025). Five schools are already operating in the Mekong River region with support from the Mekong–Korea Cooperation Fund and the Mekong Institute; each rainwater-for-drinking (RFD) system supplies roughly 500 litres of safe drinking water per day, enough to meet year-round school demand. Students actively monitor rainfall, evaluate water quality, and communicate climate knowledge within their communities through BiTS school clubs.

Outcome: safe drinking water for schools, rising climate awareness among students, and government-led national expansion.

Challenge: sustaining technical capacity and recurrent funding as the programme scales from five pilot schools toward a planned national network of 1,000.

Lesson learned: education significantly increases the long-term sustainability of decentralised water systems.

Myanmar: communities as water managers

Experiences from Myanmar demonstrate the importance of community ownership during both emergency response and long-term recovery. When a 7.7-magnitude earthquake struck on 28 March 2025, leaving more than 17 million people across 13 states and regions vulnerable as centralised water systems collapsed, the mobile rainwater-for-drinking (Mobile RFD) system was deployed as a rapidly deployable, decentralised response (Han, 2025). The system connects five tanks in series for sedimentation and natural purification, requires no electricity or chemicals, and uses a collapsible catchment that non-technical community members – particularly women – can assemble and operate independently. In a May 2025 pilot in an earthquake-affected village, just 32 millimetres of rainfall yielded more than 500 litres of usable water, managed by local women after brief instruction. The system was subsequently presented at the Mekong–Republic of Korea Cooperation Forum in Hanoi, drawing interest from Cambodia, Vietnam, Laos, and Thailand.

Outcome: rapid restoration of safe drinking water, growing community ownership, and improved long-term operation.

Challenge: converting emergency deployments into permanently managed community assets requires time, sustained facilitation, and clear rules on cost-sharing.

Lesson learned: infrastructure becomes sustainable only when communities become managers rather than beneficiaries.

India: national policy enabling large-scale implementation

India demonstrates how national policy can accelerate rainwater harvesting at scale. Programmes such as Catch the Rain and Jal Sanchay Jan Bhagidari combine government leadership with extensive citizen participation. According to Ministry of Jal Shakti (n.d) , more than seven million water-conservation and rainwater-harvesting structures had been built or renovated nationwide by 2024, alongside the geo-tagging of over 2.4 million water bodies under the country's first national water-body census.

Outcome: large-scale implementation, strong public participation, and integration into national water policy.

Challenge: independent, third-party verification of reported outcomes remains limited, and urban implementation lags behind rural progress.

Lesson learned: supportive policy frameworks enable local initiatives to expand nationally.

Tanzania: rainwater harvesting for sustainable water supply and local development

In East Africa, the Water Institute of Tanzania (WI) and its partner NTWAM Water & Environment Initiatives are pioneering community rainwater systems under the national slogan VUMME – “Vuna Maji Kwa Maendeleo Endelevu” (Harvest Water for Sustainable Development). Their work integrates technical training with gender inclusion and local enterprise, creating employment while improving domestic and agricultural water supply.

Outcome: improved domestic and agricultural water supply, growth of local enterprise, and gender-inclusive technical training that expands women's roles in water management.

Challenge: scaling beyond pilot communities depends on sustained training capacity and demand remaining strong enough to keep new enterprises viable amid seasonal rainfall variability.

Lesson learned: decentralised rainwater management is not merely a coping strategy for scarcity but a catalyst for local development, linking livelihoods with long-term sustainability.

Mexico: traditional knowledge and modern innovation

Experiences from Mexico demonstrate that traditional rainwater knowledge remains highly relevant when combined with modern engineering and public education. Rather than replacing indigenous practices, contemporary rainwater programmes build upon local experience while introducing improved treatment technologies, digital monitoring, and community engagement, producing a resilient model that combines cultural heritage with scientific innovation.

Outcome: improved urban and rural water security, preservation of traditional knowledge, and stronger community engagement.

Challenge: reconciling indigenous practices with modern regulatory standards, and uneven financing between urban pilots and rural sites.

Lesson learned: traditional knowledge becomes more valuable when combined with modern science and technology.

International networks accelerate innovation

No single country possesses all the answers to climate resilience. International collaboration through the RWHM Specialist Group, the International Rainwater Harvesting Alliance (IRHA), Rain for All (RFA), SARNET, and regional partnerships has enabled knowledge exchange across Asia, Africa, Latin America, and Europe through joint research, conferences, demonstration projects, and educational programmes.

Challenge: differences in regulatory frameworks, funding cycles, and data-sharing practices can slow joint research and replication.

Lesson learned: global collaboration significantly accelerates local innovation.

Common lessons across regions

Despite considerable differences in geography, climate, culture, and governance, these experiences reveal common lessons, summarised in Table 1.3.

Table 1.3 Comparative summary of international case studies

Country/region	Key mechanism	Outcome highlight	Key challenge
Cambodia	Rain School Initiative; MoEYS–RAC–SNU partnership	Safe school drinking water; national expansion toward 1,000 schools	Sustaining funding and capacity beyond pilot schools
Myanmar	Mobile RFD; community-based CBRD	Rapid post-disaster restoration of drinking water	Slow handover from relief agencies to resident managers
India	Catch the Rain; Jal Sanchay Jan Bhagidari	7+ million structures built/ renovated by 2024	Limited independent verification; uneven urban uptake
Tanzania	VUMME community rainwater enterprise model (WI & NTWAM)	Job creation and gender-inclusive local enterprise	Sustaining enterprise viability amid rainfall variability
Mexico	Traditional knowledge combined with modern treatment	Improved urban and rural water security	Uneven financing between urban pilots and rural sites

First, rainwater harvesting is most successful when engineering is combined with education, governance, and community participation. Second, decentralised systems complement rather than replace centralised infrastructure, increasing flexibility under climate uncertainty. Third, digital technologies and citizen science strengthen adaptive management by making monitoring more transparent and participatory. Finally, international collaboration enables successful local innovations to be adapted and replicated under different environmental and institutional conditions.

Strategic recommendations

The experiences presented in this paper demonstrate that rainwater harvesting and management has evolved beyond a supplementary water supply option into an essential strategy for climate resilience, water security, and adaptive governance. To accelerate this transition, coordinated action is required at multiple levels.

Mainstream rainwater in climate and water policies *(national governments, policymakers, regulators)*: Rainwater should be explicitly recognised as a strategic water resource within national climate adaptation plans, water security strategies, and disaster risk reduction programmes, integrated into mainstream water planning alongside conventional infrastructure.

Strengthen community-based governance *(local authorities, utilities, schools, NGOs)*: Long-term sustainability depends on community ownership rather than infrastructure alone. Schools, local authorities, NGOs, and citizens should participate actively in planning, operating, and maintaining decentralised rainwater systems, improving resilience while reducing long-term operational costs.

Invest in education and capacity building *(ministries of education, universities, training bodies)*: Rainwater harvesting should become an integral part of environmental education, engineering curricula, and professional training. The Rain School Initiative shows how schools can simultaneously improve drinking water security and develop future leaders capable of managing climate-related water challenges.

Accelerate digital transformation *(utilities, researchers, technology funders)*: Artificial intelligence, cloud-based monitoring, low-cost sensors, and citizen science platforms should become standard components of modern rainwater management, improving monitoring, supporting adaptive management, and enabling communities to participate directly in data collection and decision-making.

Expand international collaboration *(international organisations, development partners, regional networks)*: The RWHM Specialist Group should continue strengthening partnerships with governments, universities, NGOs, and regional rainwater networks to accelerate technology transfer, policy learning, and capacity development, with particular attention to South–South cooperation among similar climatic and socio-economic conditions.

Establish World Rain Day as an annual global platform *(national governments, the United Nations system)*: World Rain Day (3 September) would provide an annual international platform for promoting rainwater harvesting, climate education, policy dialogue, citizen science, and community action – encouraging governments, schools, utilities, researchers, and communities to review progress and exchange experience each year, so that annual awareness evolves into measurable climate action.

Conclusion

Climate change is transforming not only the global water cycle but also the way societies must manage water. The experiences presented in this chapter demonstrate that rainwater harvesting and management has evolved from a supplementary technology into a strategic approach for strengthening climate resilience, water security, and adaptive governance.

The paradigm proposed by the IWA Rainwater Harvesting and Management Specialist Group extends beyond engineering solutions. It integrates community participation, education, governance, digital innovation, and international collaboration into a comprehensive framework for climate adaptation. The international experiences presented from Cambodia, Myanmar, India, Tanzania, Mexico, and other regions demonstrate that decentralised rainwater management can generate practical benefits under diverse environmental, social, and institutional conditions.

Rainwater should therefore no longer be viewed simply as a source of water or as stormwater requiring drainage. It should be recognised as a strategic resource that simultaneously supports drinking water security, groundwater recharge, flood mitigation, public health, climate adaptation, and community resilience. Looking ahead, the challenge is no longer whether rainwater harvesting works, but how rapidly it can be integrated into mainstream water governance and climate policy – a transition that requires stronger partnerships among governments, international organisations, researchers, educators, communities, and the private sector.

The proposed World Rain Day represents one practical mechanism for advancing this vision. By providing an annual platform for education, policy dialogue, citizen engagement, and international cooperation, it can help transform awareness into collective action and local innovation into global impact. Ultimately, climate resilience will not be achieved solely through larger dams, longer pipelines, or more sophisticated treatment plants. It will also depend on how wisely humanity manages the rain that falls freely on every roof, every school, every village, and every city. Rainwater harvesting and management therefore represents not only a technological opportunity but a new paradigm for building a more resilient, equitable, and sustainable future.

References

Campisano, A., Butler, D., Ward, S., Burns, M.J., Friedler, E., DeBusk, K., Fisher-Jeffes, L.N., Ghisi, E., Rahman, A., Furumai, H., and Han, M. (2017) Urban rainwater harvesting systems: Research, implementation and future perspectives. *Water Research*, 115, 195–209.

Han, M. (2025) Rain for resilience. The Source, International Water Association, 24 September. Available at: https://thesourcemagazine.org/rain-for-resilience/

Han, M., and Rohilla, S. (2025) What the world can learn from Korea's 15th-century rain gauge. *The Conversation*, 4 August.

IPCC (2023) Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva.

Ministry of Jal Shakti (n.d.) Jal Shakti Abhiyan: Catch the Rain. National Water Mission, Government of India. Available at: https://nwm.gov.in/catchtherain

OECD (2015) OECD Principles on Water Governance. Adopted by the OECD Water Governance Initiative, OECD, Paris.

Yarrow-Soden, E. (2025) Rain Schools progress in Cambodia. The Source, International Water Association, 26 February. Available at: https://thesourcemagazine.org/rain-schools-progress-in-cambodia/

United Nations (2015) Transforming our World: The 2030 Agenda for Sustainable Development. UN General Assembly Resolution A/RES/70/1, United Nations, New York.

World Health Organization (WHO) (2022) Guidelines for Drinking-water Quality: Fourth edition incorporating the first and second addenda. World Health Organization, Geneva.

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Rethinking California's water crisis 'people vs fish': Coastal reservoirs for environmental protection and water supply

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Introduction: A new water paradigm

The global water crisis is intensifying rapidly. Approximately 2.2 billion people lack access to safely managed drinking water (UN Water, 2025), and more than 5 billion could face shortages by 2050 (Cusick and News, 2022). The concept of 'global water bankruptcy' (Madani, 2026) highlights a fundamental imbalance between freshwater demand and sustainable water supply.

California provides a high-profile example of this challenge. The 2025 wildfire crisis, with approximately 30 fatalities and economic losses estimated at US$250–275 billion (UNDRR, 2026), brought global attention to tensions between environmental protection and human water security. The widely publicised "people versus fish" debate between US president D. Trump and California Governor G. Newsom reflects a deeper structural issue. Under conventional land-based water management, environmental flows and human use are often treated as competing demands within a fixed water budget. Environmental flow frameworks commonly restrict extraction to approximately 40%, leaving 60% of water for ecosystems (Richter et al., 2012) and eventually lost to the sea. While ecologically necessary, this increases pressure on urban and agricultural systems or water-food-environment nexus, especially under climate variability.

Similar conflicts have emerged globally in regions such as Cape Town and Chennai, as shown in Figure 1.9. These conflicts are becoming worse because of aging land-based infrastructures like dams, aqueducts, population growth, urbanisation, and climate change. The California wildfire debate, therefore, represents not an isolated political event, but a warning sign that traditional land-based water management is approaching its practical limits. As climate variability intensifies, these conflicts are likely to reappear repeatedly in Los Angeles and elsewhere whenever another severe drought, wildfire, or extreme hydrological event occurs. Even so, billions of gallons of freshwater are discharged into the sea (Smith, 2024). The people versus fish debate, therefore, represents a global structural problem rather than an isolated local controversy.



Figure 1.9: The 'Day Zero' crises in Cape Town and Chennai demonstrate that the conflict between environmental protection and human water demand is a growing global challenge

Compounding this problem is aging infrastructure. California's major water systems (Figure 1.10), such as the Central Valley Project, State Water Project, and Los Angeles Aqueduct, were constructed largely between the 1930s and 1970s. Many components are now beyond their design life. With more than 1,500 dams in California and over 90,000 dams in the USA (average age >56 years), rehabilitation costs exceed US$64 billion nationally. Aging infrastructure increases vulnerability to extreme floods, droughts, and seismic events. These factors indicate that conventional land-based water systems are approaching their technical and environmental limits. A new paradigm is required, one that avoids zero-sum allocation and instead expands usable water resources.

Sea-based water solutions, particularly coastal reservoirs and interconnected seabed pipelines, offer a potential pathway toward coexistence and a win–win future by capturing excess freshwater before it is lost to the ocean while maintaining upstream environmental flows intact.

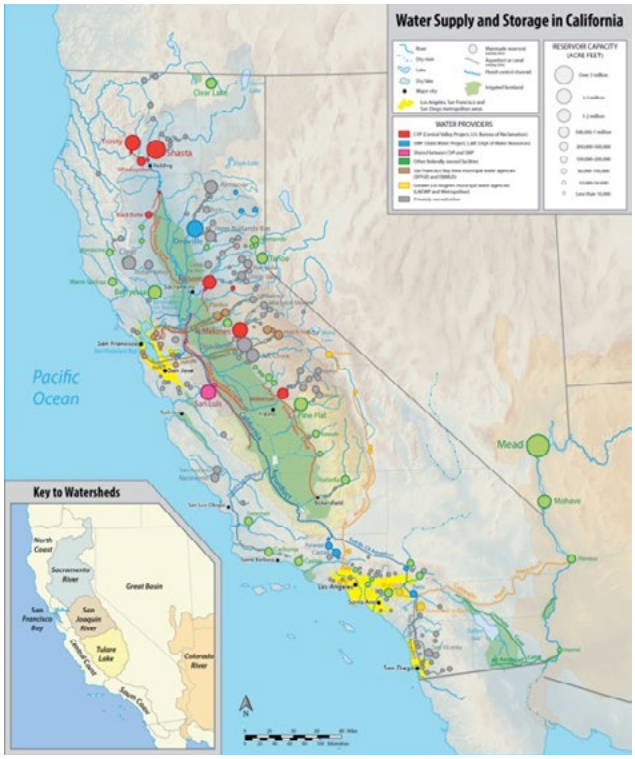


Figure 1.10. Major water facilities as well as major rivers and cities in California





Figure 1.11a: Singapore Marina Coastal Reservoir (above)
Figure 1.11b: Shanghai Coastal reservoirs (below)

Sea-based water solutions: a win–win pathway for 'people and fish'

Sea-based water solutions (Yang, 2022) represent a fundamental shift in water management, from upstream interception to downstream recovery. Unlike dams and aqueducts that divert water before it reaches ecosystems, coastal reservoirs are located near river mouths, allowing environmental flow requirements to be fully met before excess water is captured. This approach transforms the water allocation framework. Instead of dividing limited freshwater between human and environmental uses, it captures surplus runoff that would otherwise flow into the ocean. Consequently, environmental protection and water supply are no longer inherently in conflict.

The international experience demonstrates the viability of this concept in several major coastal cities. Singapore's Marina Barrage (Figure 1.11a) is one of the world's best-known examples of integrated sea-based water management (Tan and Ng, 2021) that combines drinking water supply, flood control, recreation, and environmental enhancement within a single coastal reservoir system. Shanghai's Qingcaosha Coastal Reservoir (Figure 1.11b) provides another large-scale example (Yang, 2005). It supplies freshwater to approximately 25 million people by capturing water near the Yangtze River mouth while preserving upstream ecological integrity. By capturing freshwater after environmental flows have passed through the river system, Qingcaosha illustrates how coastal reservoirs can support megacity water security without intensifying conflicts between ecosystems and urban users.

In addition to storage, seabed pipelines provide a modern alternative to inland conveyance systems. Compared with canals and aqueducts, they offer minimal evaporation losses, reduced land acquisition and pumping requirements, lower ecological disruption and improved resilience to climate variability and seismic risk.

Together, coastal reservoirs and seabed pipelines form an integrated system capable of delivering a large-scale water supply while maintaining environmental flows. This concept has been proposed for California (Figure 1.12) by Yang (2022), and its technical, environmental, and economic feasibility is explored below.



Figure 1.12 Proposed interlinked coastal reservoirs to secure California water supply.

Feasibility of California's sea-based water solution

California's water challenge is not simply one of scarcity, but of misaligned capture and distribution. The state receives over 200 km³ of precipitation annually, with approximately 60–80 km³/year of runoff reaching the Pacific Ocean (Figure 1.13). By comparison, total domestic demand is only about 10.6 km³/year. Even harvesting a small fraction of runoff currently discharged to the sea could substantially strengthen long-term water security for coastal cities.

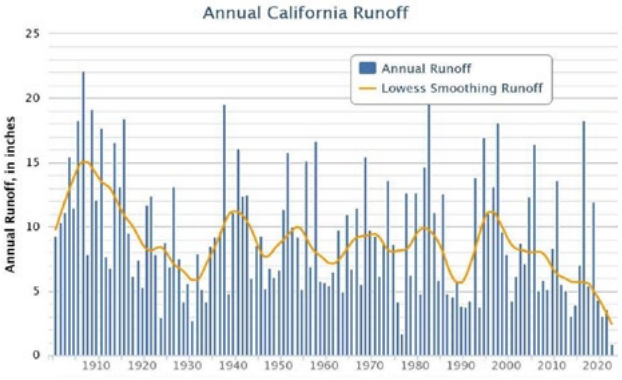


Figure 1.13: Annual California runoff from 1900 to 2021

Southern California represents the region with the greatest imbalance between local water availability and population demand. Los Angeles is a dry coastal megacity with an average annual rainfall of only about 384 mm/year. Historically, the city relied on the Los Angeles River, an approximately 80 km long river with a catchment area of about 2,100 km² and an annual runoff estimated at only 240 GL/year. As population and industrial growth accelerated in the early twentieth century, local water resources quickly became insufficient, leading to the construction of one of the world's largest land-based water diversion systems.

The Los Angeles Aqueduct, completed in 1913, diverted water over more than 400 km from the Owens River to Southern California. This system was later expanded to include water from the Mono Basin in 1940, followed by the Colorado River Aqueduct in 1970. Before 1980, Los Angeles obtained most of its imported water from Owens Valley and Mono Basin, with the imported supply reaching approximately 620 GL/year and the total city supply about 755 GL/year. However, growing environmental degradation in Owens Lake and Mono Lake – including ecosystem collapse, dust storms, and habitat loss – forced substantial reductions in water diversion. Between 1990 and 2000, imported water from Owens Valley and Mono Basin declined from about 620 GL/year to approximately 370 GL/year to reduce environmental impacts. To compensate, imports from the Colorado River and California's Central Valley increased significantly, while local groundwater contributed about 110 GL/year.

Despite these expansions, Los Angeles remained vulnerable during the extreme 2012–2016 California drought, when total municipal supply fell to approximately 602 GL/year. Meanwhile, the metropolitan population increased from about 3.8 million in 2000 to nearly 4.8 million by 2020, placing further pressure on already stressed water systems. The statewide drought caused economic losses estimated at approximately US$2.74 billion in 2015 alone, with agriculture accounting for nearly two-thirds of total damages due to reduced irrigation supplies and groundwater depletion.

California's existing water infrastructure remains one of the world's largest engineered systems. The Central Valley Project alone stores approximately 16 km³ of water in more than 20 dams and diverts over 9 km³/year toward Southern California through the 640 km California Aqueduct (Chung et al., 2002). However, much of this infrastructure is aging, environmentally constrained, energy-intensive, and increasingly vulnerable to climate extremes and seismic risks. Sea-based water solutions based on coastal reservoirs and interconnected seabed pipelines, therefore, represent not simply an additional water source, but a new paradigm for sustainable coexistence between environmental protection and human development.

After more than a century of intensive inland water development, opportunities for additional large-scale upstream diversion projects are becoming increasingly constrained by environmental regulations, aging infrastructure, escalating costs, and ecological protection requirements. Under these conditions, sea-based water solutions provide a potentially transformative alternative.

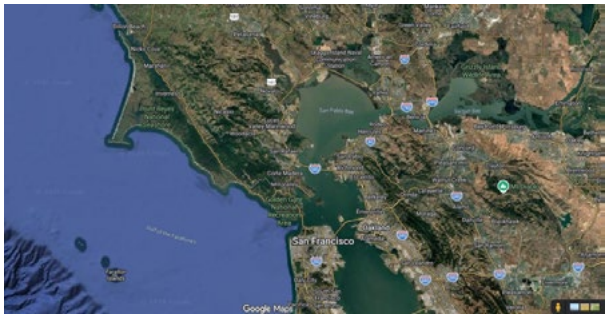
At the local scale, a coastal reservoir near the mouth of the Los Angeles River could capture between 160 and 240 GL/year of freshwater currently discharged into the Pacific Ocean during storms and wet years. Considering that Los Angeles' annual water demand is approximately 600 GL/year, even partial recovery of this runoff could significantly improve urban water resilience.

The largest opportunity, however, lies in Northern California. The Sacramento and San Joaquin Rivers generate the majority of California's freshwater runoff, with combined annual flows exceeding 38 km³/year from their catchment over 100,000km². Although the Central Valley Project and State Water Project currently divert large volumes southward, substantial quantities of freshwater still flow through San Francisco Bay into the Pacific Ocean after environmental flow requirements are satisfied.

A strategically located coastal reservoir near the Sacramento–San Joaquin Delta and San Francisco Bay, as shown in Figure 1.14 could intercept part of this excess freshwater before seawater mixing occurs. These reservoirs could then be connected to Southern California through a large-diameter seabed pipeline extending approximately 625 km along the Pacific coastline from San Francisco to Los Angeles. Such a pipeline would be comparable in length to the existing Los Angeles Aqueduct but potentially with lower environmental impact, lower evaporation losses, reduced land acquisition and pumping requirements, and greater climate resilience.

Conceptually, the San Francisco Bay coastal reservoir system could utilise existing lagoon and bay geometries in San Pablo Bay and Grizzly Bay to minimise land inundation and environmental disturbance. Barrages and gated structures could regulate freshwater inflows, prevent seawater intrusion during wet periods, and release excess flows during floods to maintain estuarine stability. During high-flow events, the best-quality freshwater could be selectively stored for urban use, while lower-quality water and wastewater could continue flowing to the sea when necessary. A reservoir area of approximately 300 km² with an average depth of only 2 m would provide approximately 600 GL of storage capacity, substantially improving drought resilience for both the Bay Area and Southern California.

California's high seismic risk introduces additional challenges for traditional infrastructure. Inland aqueducts, elevated canals, and dams are vulnerable to ground rupture, differential settlement, and structural fatigue. In contrast, coastal reservoirs and seabed pipelines offer improved seismic resilience. Pipelines can be flexibly designed to accommodate seabed movement. Offshore or shallow coastal systems are less exposed to fault rupture compared to inland structures, and distributed coastal storage reduces reliance on a few large, high-risk inland dams. Thus, sea-based systems provide not only hydrological and environmental advantages but also improved risk resilience in earthquake-prone regions.



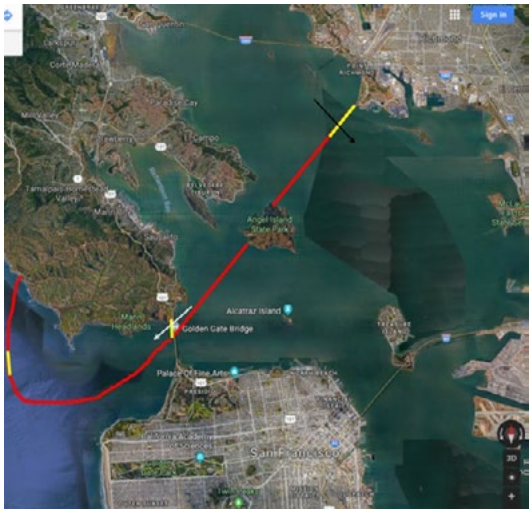


Figure 1.14a (above): Proposed coastal reservoirs in bays (seawall in red, gates in yellow)

Figure 1.14b (below): Alternative proposal outside river mouth (white= high quality, black= poor quality water)

Comparison between land-based and sea-based water diversion systems

California's existing water supply system is dominated by land-based infrastructure, particularly the Central Valley Project (CVP), State Water Project (SWP), and the California Aqueduct. These systems transfer freshwater from Northern California to Southern California through an extensive network of dams, canals, pumping stations, and aqueducts extending over 600 km. While this infrastructure enabled California's economic development in the twentieth century, it is increasingly constrained by environmental, economic, and operational limitations.

In contrast, the proposed sea-based system captures excess freshwater near the Sacramento–San Joaquin Delta and San Francisco Bay after environmental flow requirements are satisfied. This water is then transported to Southern California through interconnected seabed pipelines extending approximately 625 km along the Pacific coastline. This approach represents a fundamental shift from upstream diversion to downstream recovery.

A key distinction between the two systems lies in their treatment of environmental flows. Land-based diversion systems intercept freshwater upstream, directly reducing flows to downstream ecosystems, thereby intensifying the conflict between environmental protection and water supply. In contrast, sea-based systems allow rivers and estuarine ecosystems to receive 100% environmental flows before surplus water is captured. In this sense, ecosystems "use the water first", significantly reducing the people versus fish conflict.

The Sacramento and San Joaquin Rivers generate more than 38 km³/year of runoff, while large quantities of freshwater continue flowing through San Francisco Bay into the Pacific Ocean after environmental requirements are met. Capturing only part of this excess freshwater could potentially provide over 10 km³/year of water for Southern California, substantially exceeding current municipal demand as shown in Figure 1.15. By comparison, the California Aqueduct currently diverts approximately 9 km³/year (Cooley, 2020) through one of the world's most energy-intensive inland water transfer systems.

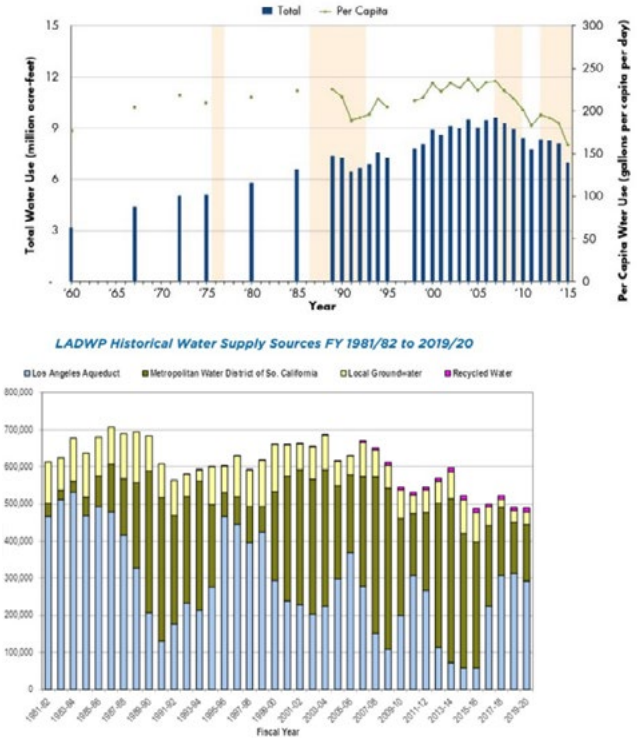


Figure 1.15: Historical water use in California (above) and Los Angeles (below)

In terms of conveyance, inland aqueduct systems require extensive land corridors, are subject to evaporation losses, and often traverse seismically active and environmentally sensitive areas. By contrast, seabed pipelines offer several advantages. They operate as enclosed pressurised systems with minimal evaporation loss, require little land acquisition, and avoid habitat fragmentation associated with open canals. Coastal routes are also less constrained by urban development and agricultural land use.

Table 1.4 shows the principal differences between California's traditional land-based diversion system and the proposed sea-based water solution linking San Francisco and Los Angeles.

To explore these possibilities, two scenarios are considered:

1. A single CR capturing runoff from the Los Angeles and Santa Ana Rivers, linked to an existing desalination facility.
2. Two CRs – one at San Francisco and one at Los Angeles – connected by seabed pipelines to facilitate regional redistribution.

Table 1.4 Comparison between California's land-based and proposed sea-based water diversion systems

Item	Land-based water diversion	Sea-based water solution
Main concept	Upstream river diversion through dams and aqueducts	Downstream coastal storage after environmental flows
Main infrastructure	Dams, canals, aqueducts, pumping stations	Coastal reservoirs and seabed pipelines
Water source	upstream	Excess freshwater near San Francisco Bay
Water transfer route	Inland California Aqueduct	Coastal seabed pipeline
Approximate conveyance length	~640 km	~625 km
Environmental flow impacts	Direct competition between ecosystems and water supply	Environmental flows maintained before storage
People vs fish conflict	High	Significantly reduced
Evaporation losses	High in open canals	Minimal in enclosed pipelines
Land acquisition	Extensive	Minimal
Habitat fragmentation	Significant	Relatively low
Seismic vulnerability	High across the inland infrastructure	Lower along seabed routes
Infrastructure age	Many components >50–100 years old	New system with modern design
Climate resilience	Increasingly vulnerable to drought and heat	Higher resilience to climate extremes
Potential ecological benefits	Reduced downstream flows	Potential restoration of inland ecosystems
Potential annual supply	~9 km^3/year diverted south	Potentially >10 km^3/year
Key examples	California Aqueduct, LA Aqueduct	Shanghai Qingcaosha, Singapore Marina Barrage

Shanghai's Qingcaosha CR serves as a benchmark, with a surface area of 66.15 km², storage capacity of 527 GL, and daily supply of 6.6 GL. Its 48.4 km dyke includes two sluices and cost ¥6.45 billion (≈ US$1.0 billion) in 2010.

Based on this model, estimated costs for California include:

- **Scenario 1:** US$1.0 billion for one CR at Los Angeles (desalination plant already built)
- **Scenario 2:** US$2.0 billion for two CRs, plus US$5.5 billion for seabed pipelines

For Shanghai, its complete sea-based system—CRs, pipelines, and pumps—cost at ¥17 billion (≈ US$2.6 billion). The water network would include eight water treatment plants (16.17 GL/day capacity), 36 public treatment works (11.45 GL/day), and 30,000 km of distribution pipes (Li et al., 2019).

Singapore's fourth desalination plant uses CR water and seawater, operating at S$1.08/m³ (≈ US$0.82/m³) – a reference for Scenario 1 (Tan and Ng, 2021). Singapore's integrated CR-desalination system, already operational, proves that combining sea-based storage with modern treatment technology reduces energy and enhances system resilience.

Table 1.5 illustrates that sea-based solutions offer significantly higher yields at lower cost and with less environmental impact. For example, California's proposed water tunnel is expected to cost approximately US$20 billion to deliver about 0.5 km³/year. By comparison, a coastal reservoir system at Los Angeles is estimated to cost around US$1 billion and could deliver approximately 0.92 km³/year, nearly twice the volume at only 5% of the cost.

Table 1.5. Comparison of land-based and proposed sea-based water solutions for Southern California

Solution	Construction cost (US$b)	Max. supply (km³/yr)	Environmental. impact	Estimated operational cost (US$/m³)
1 CR at LA	1.0+0(desalination)	0.92	minimum on fish (delta smelt) or groundwater	0.82
2 CRs at LA & San Francisco	2.0+5.5 (seabed pipelines)	10.6	minimum on fish (delta smelt) or groundwater	Same as the Aqueduct
Los Angeles Aqueduct	(existing)	0.62	Very high	N.A
California Aqueduct	Additional 20 billion for a tunnel	≈additional 0.5	Very high	N.A.
Colorado River Aqueduct	Existing	1.48	Very high	N.A.
Groundwater recharging	0.3/yr	0.37	Minimum	N.A.
Wastewater reuse	N.A.	0.048	Minimum	N.A.

The Nord Stream 2 seabed pipeline – from Russia to Germany – costs approximately US$11 billion and spans 1,230 km (Crowley, 2022). Given that the distance between San Francisco and Los Angeles is about half that, a comparable freshwater transfer system, including pumping stations, is estimated at around US$5.5 billion, as noted in Table 1.5. With careful planning and environmentally sensitive design, coastal reservoirs can be implemented with minimal ecological disruption – even to vulnerable species such as the Delta smelt.

California's land-based water diversion projects tend to be more expensive and capital-intensive. The Los Angeles Aqueduct, measuring 674 km in length with a 3.7-meter diameter, delivers up to 620 GL/year. The California Aqueduct, which stretches 715 km, is the subject of a proposed US$20 billion tunnel project (James, 2024). Without this tunnel, water deliveries are projected to decline by 22% by 2070. If completed, the tunnel could provide an additional 400,000 acre-feet (≈0.5 km³) of water annually, as reflected in Table 1.5. Additionally, the Colorado River Aqueduct extends 389 km and supplies approximately 1.48 km³/year.

Importantly, sea-based solutions are not intended to replace all existing systems but to complement them. Groundwater recharge, wastewater reuse, and stormwater capture remain important components of California's water strategy. For example, groundwater has historically provided up to 23% of Los Angeles's supply, while stormwater capture initiatives aim to recover up to 370 GL/year by 2045, supported by a dedicated parcel tax generating approximately US$300 million annually

(Becker, 2024). Wastewater reuse currently contributes about 48 GL/year. Integrating coastal reservoirs with these measures can create a more diversified and resilient supply system.

It is also evident from Table 1.5 that sea-based water solutions clearly outperform land-based options in terms of water volume, cost-efficiency, and environmental footprint. For instance, the proposed California water tunnel is expected to cost US$20 billion to deliver 0.5 km³/year of water. In contrast, a single coastal reservoir system can provide 0.92 km³/year at just US$1 billion – nearly twice the volume at only 5% of the cost. Additionally, sea-based solutions can indirectly enhance upstream water availability for agriculture by reducing reliance on traditional water transfers. The tunnel, designed to span 45 miles (72 km) and 36 feet (11 meters) in diameter, can transport over 161 million gallons of water per hour. Meanwhile, the coastal reservoir-desalination model, successfully adopted in Singapore, has demonstrated a substantial reduction in energy use and operational costs by utilising partially fresh runoff instead of seawater as feedstock.

Finally, implementation considerations favour sea-based approaches. Large inland infrastructure projects in California often face prolonged permitting processes, legal disputes, and land acquisition challenges. The proposed water tunnel, for example, has encountered significant political and environmental opposition. In contrast, coastal reservoir projects can be constructed more rapidly with fewer social disruptions. Shanghai's Qingcaosha Reservoir was completed within approximately two years, while Nord Stream 2 pipeline was constructed between 2018 and 2021.

Overall, the comparison indicates that sea-based water systems offer a compelling alternative to traditional land-based diversion infrastructure. They provide higher water yield, lower environmental impact, improved energy efficiency, reduced lifecycle cost, and enhanced resilience to climate and seismic risks. By shifting the focus from upstream diversion to downstream recovery, coastal reservoirs and seabed pipelines offer a pathway toward resolving the long-standing conflict between environmental protection and human water supply.

Conclusions

The "people versus fish" debate reflects a broader global challenge in water management. Conventional systems increasingly force environmental protection and human demand into direct competition. Climate change, infrastructure aging, and population growth are intensifying this conflict. This study shows that California is not fundamentally water-scarce. Large quantities of stormwater runoff continue to flow unused into the Pacific Ocean. The key issue lies in how water is captured and managed.

Coastal reservoirs and seabed pipelines provide a viable and transformative alternative. By capturing water after environmental requirements are met, they enable a coexistence model in which ecosystems and human users both benefit. In addition to higher water yield and lower environmental impact, sea-based systems offer improved energy efficiency, lower lifecycle cost, enhanced climate resilience, and superior seismic robustness in earthquake-prone regions.

International experience in Singapore and Shanghai confirms that these systems are technically feasible and adaptable to complex urban environments.

Further research is required in water quality, sedimentation, ecological impacts, and marine permitting. However, the concept represents a critical shift toward integrated and resilient water management. Rather than continuing the recurring debate over people or fish, future strategies should focus on achieving both. Coastal reservoirs provide a practical, scalable, and forward-looking pathway to realise this goal.

References

Becker R. (2024), Capturing storm runoff could supply water to millions of Californians a year, Study finds". KQED, Feb. 29, https://www.kqed.org/news/11977573/californias-urban-runoff-flows-down-the-drain-can-the-drought-plagued-state-capture-more-of-it.

Chung, Francis; Kelly, Katherine; Guivetchi, Kamyar (2002). "Averting a California water crisis". *Journal of Water Resources Planning and Management*. 128 (4): 237–239. doi:10.1061/(ASCE)0733-9496(2002)128:4(237).

Cooley, H. (2020). Urban and Agricultural Water Use in California, 1960-2015. Oakland, Calif.: Pacific Institute. https://pacinst.org/wp-content/uploads/2020/06/PI_Water_Use_Trends_June_2020.pdf.

Crowley M. (2022), U.S. says $11 billion Nord Stream 2 pipeline will not move forward if Russia invades Ukraine. *The New York Times*, Jan. 28, https://www.nytimes.com/2022/01/28/world/europe/nord-stream-2-ukraine-russia.html.

Cusick D. & and News E. E. (2022), 5 billion people will face water shortages by 2050, *Scientific American*. https://www.scientificamerican.com/article/5-billion-people-will-face-water-shortages-by-2050-u-n-says/

James, I. (2024), Newsom administration unveils new $20-billion cost estimate for delta water tunnel, *Los Angeles Times*, May 16, https://www.latimes.com/environment/story/2024-05-16/california-water-tunnel-cost-estimated-at-20-billion.

Li, M.; Chen, J.; Finlayson, B.; Chen, Z.; Webber, M.; Barnett, J.; Wang, M. (2019). Freshwater supply to metropolitan Shanghai: Issues of quality from source to consumers. *Water*, 11, 2176. https://doi.org/10.3390/w11102176.

Madani, K. (2026). Global water bankruptcy: Living beyond our hydrological means in the post-crisis era. United Nations University Institute for Water, Environment and Health (UNU-INWEH), Richmond Hill, Ontario, Canada. DOI: 10.53328/INR26KAM001

Richter, Brian, Davis, M., Apse, Colin, & , Konrad, Christopher. (2012). A presumptive standard for environmental flow protection. *River Research and Applications*. 28. 10.1002/rra.1511.

Smith H. (2024), California is letting billions of gallons of stormwater wash out to sea each year, report finds. Climate & Environment, *Los Angeles Times*, March 1, https://www.latimes.com/environment/story/2024-03-01/california-missing-out-on-billions-of-gallons-of-stormwater.

Tan A. and Ng K. G. (2021), Singpore's fourth desalination plant, which can treat both sea and reservoir water, officially opens, *The Straits Times*, Feb. 05, https://www.straitstimes.com/singapore/singapores-fourth-desalination-plant-officially-opens-can-treat-both-sea-and-reservoir.

UNDRR (2026), The invisible costs of wildfire disasters in 2025, https://www.undrr.org/news/invisible-costs-wildfire-disasters-2025.

UN-Water (2025), Water Facts, https://www.unwater.org/sites/default/files/2025-01/UN-Water_Water_Facts_one_pager_January_2025.pdf

Yang, S.Q., (2005), “Completely solve water shortage problem in Shanghai by coastal reservoirs” (http://www.paper.edu.cn/releasepaper/content/200508-130).

Yang, S.Q. (2022), *Coastal reservoir technology and applications*, Elsevier.

| 1.10 |

Water Security & Safety Management: overview from the IWA Specialist Group

Author: *Prof Amit Chanan on behalf of the IWA Specialist Group on Water Security & Safety Management*

Introduction

The Water Security & Safety Management (W2SM) Specialist Group defines modern water security through the lens of best-practice assessment, robust risk management, and the rapid deployment of emerging technological solutions. Our scope spans preventive measures, early detection, and the complex logistics of post-disaster recovery, addressing both natural disasters and man-made threats.

As the IWA water community prepares for the 2026 World Water Congress in Glasgow, the W2SM Specialist Group is focusing on practical approaches to building resilience. Our vision of resilience is proactive, digital, and systemic. In an era where stationarity is dead and hydrological extremes are the new norm, the W2SM Specialist Group is providing thought-leadership to pivot the industry from traditional risk assessment to this proactive, digital, and systemic approach. Our recent work bridges the gap between high-level governance and frontline operations to ensure water systems can withstand both climate-induced shocks and sophisticated, emerging technical threats.

The following update highlights our recent thought-leadership at the Efficient 2025 Conference in Melbourne, our high-level policy advocacy with the UNESCO Megacities Alliance in Paris, and outlines a strategic roadmap for safeguarding critical infrastructure against the rising tide of cyber-physical threats.

Management Committee of the W2SM Specialist Group

Chair: Dr. Amit Chanan, *Australia*
Co-Vice-Chair: Ms. Mara Ramos, *Brazil*
Co-Vice-Chair: Mr. Abdullahi Hassan Hussein, *Canada*
Secretary: Prof. Ilan Juran, *USA*
Communication Officer: Ms. Niloofar Sadeghy, *Iran*
Immediate Past Chair and Management Committee Member: Mr. Bruno Nguyen, *France*
Management Committee Member: Mr. Gérard Luyet, *Swizerland*
Management Committee Member: Mr. Ayoade Adegbite, *Nigeria*

At the 2026 IWA World Water Congress in Glasgow, the W2SM Specialist Group will open a call to refresh its Management Committee, with a strong focus on bringing in new members from the Young Water Professionals community and currently unrepresented regions globally.

2025 activities

Virtual reality-driven crisis management training at efficient 2025 in Melbourne

An area of emerging risk for most water utilities is the gap in security maturirty across its operating environment, while IT (information technology) security is maturing, OT (operational technology) – the systems that physically control water pumps and valves – remains precariously exposed. The frequency and associated costs of cybercrime targeting real-time water services have reached an all-time high.

The ATHENA project is a European-led consortium designed to enhance water service resilience through specialised preparedness. One of the lessons from the ATHENA project (which W2SM Specialist Group participated in) is that traditional classroom training is insufficient for the high-stress environment of a cyber-physical breach.

The 12th IWA Conference on Efficient Urban Water Management (Efficient 2025) in Melbourne served as the primary IWA event for the W2SM group in 2025. Under the moderation of Bruno Nguyen and and Bérengère Sixta (SUEZ), we conducted a landmark workshop: "Development of Cybersecurity Trainings for Water Utilities: The ATHENA EU Research Project".

The Melbourne workshop demonstrated the use of virtual reality (VR) combined with e-learning to simulate cyber-attack scenarios. This pedagogical shift allows operational staff to experience the "fog of war" during a crisis. The WSSM group outlined a three-phase safety model within these VR environments:

Prevention: immersing staff in "vulnerability hunts" within a digital twin of their utility

Detection: Training the "human sensor" to recognise subtle anomalies in flow and pressure that automated systems might miss during a sophisticated hack

Mitigation: Real-time decision-making exercises where participants must isolate compromised segments of the network while maintaining emergency supply to hospitals and critical sites.

The session concluded with a live "debrief" where VR performances were projected for the audience, fostering a global dialogue on the "Human Factor" in water safety.

Global policy and megacity resilience: MAWAC-ENA 2025 (Paris)

While Melbourne focused on the operational "front lines," the W2SM group's representation at the UNESCO Megacities Alliance for Water and Climate (MAWAC-ENA) Workshop in Paris (2025) addressed the governance of "super-urban" environments. Represented by Ilan Juran, Amit Chanan, and Bruno Nguyen, the W2SM group contributed to the Europe and North America (ENA) chapter of the Megacities Alliance for Water and Climate. In the high-density context of megacities, safety management must be integrated into the very fabric of urban planning.

The Paris sessions focused on several key thematic pillars:

Systemic interdependency: In a megacity, water security is tied to energy security, transport, and public order. Our group advocated for "Integrated Urban Water Management" (IUWM) data sets that are quality-assured and shareable across municipal departments during emergencies.

Climate adaptation in real-time: The W2SM group presented findings on how megacities are moving away from static 10-year plans toward "Dynamic Water Safety Plans" that utilise AI to adjust treatment parameters in response to sudden raw-water quality shifts caused by upstream climate events.

The Management Committee of W2SM SG held virtual meetings twice by zoom in 2025 and members of the management committee have contributed through reviewing abstracts and workshop proposals for the IWA WWC2026.

2026 perspectives

Looking into the strategic roadmap for the 2026 in the lead up to the Glasgow Congress, W2SM Group will be focusing its thought-leadership and participation in the following emerging priorities:

- **Cyber-physical security management:** Increasing sector awareness of cyber security risks involving the security of OT systems – the digital controls that run pumps, treatment plants, and networks and treating these checks as critical step in water safety planning.
- **Capacity building 2.0:** With success of VR based training in Melbourne, W2SM will explore further partnerships and collaborations to move beyond webinars and conventional workshops towards adopting VR training modules to utilities.
- **More multilateral collaboration:** Strengthening our ties with MAWAC to ensure that water safety and security is a central theme of the UN Sustainable Development Goal (SDG) 6 mid-term reviews. At the same time, at more practical level establishing a "Megacity-to-Emerging-City" knowledge-exchange pipeline, enabling security lessons sharing with rapidly growing urban centres in the Global South, fostering global equity in climate-informed water safety.

W2SM is a multidimensional Specialist Group, given our work cuts across many parts of the water sector. As such a stand-alone event for the SG is unlikely to deliver the breadth or impact we want. Instead, as in previous years, we will continue to work closely with other IWA Specialist Groups – especially Efficient Urban Water Management and Water Loss to create workshops and joint sessions, share technical expertise, and contribute to the wider IWA community.

On that front, Mara Ramos actively collaborated with the organisers of IWA Water Loss 2026 event in Brazil. She served as Chair, and led a landmark workshop that bridged the gap between the Water Loss and Water Security & Safety Management (W2SM) groups. By exploring physical water leaks and their direct impact on global water security, workshop demonstrated great synergy between IWA specialist groups.

| 1.11 |

Treatment wetland technology and water security

Authors: *Alexandros Stefanakis and Florentina Zurita Martínez on behalf of the Wetland Systems for Water Pollution Control Specialist Group*

Introduction

Water scarcity is one of humanity's most pressing and rapidly escalating crises. Conservative estimates suggest that nearly two-thirds of the world's population experiences at least one month of severe water scarcity annually (Muduli et al., 2024). This global challenge is driven by several interconnected factors: zero or inadequate wastewater treatment pollutes this vital resource; population growth significantly increases the demand (Santos et al., 2024); and climate change exacerbates the problem by causing devastating droughts and altering precipitation characteristics. The result is growing water stress and scarcity in many regions, particularly in developing areas, hindering the achievement of Sustainable Development Goals (SDGs) worldwide.

Water availability is fundamentally linked to almost all SDGs; therefore, addressing water-related challenges should be central to all initiatives aimed at promoting the SDGs and water security. The appropriate treatment of wastewater – both to protect water resources and for the reuse of treated water – is a critical option for mitigating water scarcity. In this context, treatment wetlands (TW) have emerged and gained recognition as a reliable and climate-resilient infrastructure for the treatment of wastewater worldwide. TWs are classified as nature-based solutions (NBS), which utilise natural processes to solve environmental and societal challenges. Essentially, TWs are engineered ecosystems that mimic the functions of natural wetlands to remove pollutants from wastewater.

TWs are today established as a treatment technology with increasing worldwide adoption (Addo-Bankas et al., 2024). The intensive and in-depth research of recent decades has led to better comprehension of the mechanisms responsible for pollutant transformation and removal, not only for conventional but also emerging pollutants, and innovations to overcome their limitations. Nowadays, TWs can be applied to almost all types of effluents. Innovation in TW technology has diversified its use, positioning it as a tool for circular water management. This contributes not only to water security (SDG6) but also to other SDGs such as SDG12.

The Wetland Systems for Water Pollution Control SG is focused on TW-related issues:

1. to improve the understanding of fundamental interactions amongst water, soil/substrate, plants, and micro-organisms inside TW that are used to control, transform and reduce pollution in the water cycle
2. to explore innovative applications and realise the full potential of TW technology worldwide
3. to mainstream TW technology within the larger field of wastewater and water pollution control
4. to define guidelines for proper design, implementation, and operation of TW; and
5. to facilitate and promote research activities for the continuing development and advancement of TW technology.

Key terminology

TWs are a group of ecological engineering systems used for water and wastewater management. TWs are multifunctional systems offering a series of ecosystem services that go beyond the basic goal of wastewater treatment and water quality improvement, including, but not limited to, biodiversity enhancement, rainwater retention, flood risk alleviation, reduced stress on local water resources, increased food production, microclimate regulation, habitat creation, and recreational areas. A modern approach integrates TW technology with a circular water economy to create synergies for the valorisation and reuse of effluents and recovery of resources. Cities that want to become more climate-resilient are making it a top priority to increase investments in NBS such as TWs to address the social, economic, and environmental challenges they are facing.

Our SG mainly focuses on TW for water pollution control, but our members are expanding towards the use of other NBS

where plants and natural processes are used such as green walls, green roofs, biofilters, bioretention systems, swales, and raingardens for water pollution control.

TW typically consist of a lined excavated basin filled with a filter medium that supports wetland vegetation. TWs are generally classified into two main types: free water surface (FWS) and subsurface flow (SSF) TWs (Stefanakis et al., 2014). In FWS TWs, a water column is maintained above the substrate (typically soil) and can operate with either floating or emergent vegetation. In SSF TWs, wastewater flows through the filter medium, and the water level is maintained below the surface. SSF TWs are further divided by flow direction: Horizontal flow (HF) and vertical flow (VF) TWs. In HF TWs, the flow is continuous, while in VF TWs the wastewater is applied intermittently across the surface and drains vertically through the filter to the bottom. The latest advance in TW design is the aerated wetland, where artificial aeration is provided to the bed (either horizontal of vertical) to enhance the aerobic removal processes and, thus, increase the treatment capacity and reduce the area demand (Nivala et al., 2020). A special design and application of TWs is also applied the dewatering of municipal sludge (Stefanakis et al., 2014; Larsen et al., 2018).

Key insights

Filter media and vegetation

TWs key components include the substrate media, vegetation, and the microbial communities that develop on it. These three elements, together, determine the degree of pollutant removal through physical, chemical, and biological processes. The filter medium not only provides structural support to the vegetation but also actively contributes to pollutant removal. It facilitates the removal both indirectly (by supporting the development of diverse microbial communities) and directly through filtration, ion exchange, and adsorption. Traditionally, filter media consists mainly of fine to coarse gravel and sand. However, recent research has increasingly reported the use of novel materials such as biochar (Zhuang et al., 2022), construction waste, such as bricks and crushed concrete (Muduli et al., 2024), and recycled plastic and biocarriers (Tatoulis et al., 2017).

The vegetation is arguably the most determinant component of TWs. While traditional species (primarily *Typha*, *Scirpus*, and *Phragmites* genera) remain in use globally, many countries have diversified their selection. In Latin America and the Caribbean (LAC) countries (such as Colombia, Mexico, Chile, and Ecuador), flowering ornamental species are now common (Zamora-Castro et al., 2025). In general, the use of well-adapted local species has proven effective in ensuring the efficient performance of TWs.

Emerging pollutants

Pharmaceuticals and personal care products have been extensively evaluated in various TWs for nearly two decades (Lv et al., 2016; Chen et al., 2017; Matamoros et al., 2017; Tondera et al., 2019). The reported removal efficiencies vary widely, typically achieving higher values for readily biodegradable compounds. Key removal mechanisms include plant uptake and biotransformation (which are species-dependent), sorption/adsorption onto the substrate and organic matter, and microbial biodegradation under both aerobic and anaerobic conditions (Hou et al., 2025). Microplastics (MPs) are pollutants of great concern in water due to their persistence and resistance to biodegradation. Generally, MP removal is considered high in TWs and has been a key area of evaluation in recent years. A recent study reported removal efficiencies of around 97% in two types of small-scale TWs (VF and HF) (Wang et al., 2024), highlighting that retention in the substrate and ingestion by macroinvertebrates were significant removal factors.

Per- and polyfluoroalkyl substances (PFAS) represent one of the recent pollutant groups of highest concern. Their removal has been recently evaluated in TWs. Studies report that the efficiency of TWs in PFAS removal varies, ranging from 21.3% to 98%, depending on the TW type and the specific PFAS compound (Savvidou et al., 2024). Vegetation, depending on the species, can take up and accumulate PFASs in their roots or biomass; however, the substrate contributes to removal primarily through the adsorption of long-chain PFASs. Additionally, biotransformation of these compounds may also occur (Li et al., 2024).

New applications

Domestic and municipal wastewater has traditionally been the primary water source treated in TWs. The upper size limit of municipal wastewater TWs is now larger than previously thought. Ishtiaq et al. (2025) reports the design and implementation of a TW treating wastewater from a city of 80,000 in habitants in Saudi Arabia, which is at the moment the largest such TW application. Another large system in Moldova treats wastewater from a community of 20,000 people (Masi et al., 2017).

Due to the comparatively lower cost of TW compared to conventional technologies, there is significant increase of TW application for various industrial effluents. Studies have explored its successful use for treating tequila vinasse (wastewater) for irrigation purposes (Montoya et al., 2023), wastewater from a glass manufacturing industry (Gholipour et al., 2020), for the oil and gas industry and refineries (Stefanakis et al., 2018; Mozaffari et al., 2021; Bafrani et al., 2024), and dewatering of industrial sludges (Nielsen and Stefanakis, 2020).

TWs and the circular economy

With growing water scarcity, the focus has shifted toward using TWs to generate water for reuse (e.g. Šereš et al., 2021) and enhance the circular aspects of TW technology. It is now established that TW have a high potential to contribute to circular economy approaches (Masi et al., 2018) and the food–water–energy nexus (Avellán and Gremillion, 2019). Our SG members also contributed treatment wetland expertise to a recent COST action (implementing nature-based solutions for creating a resourceful circular city; https://circular-city.eu/), which brought together experts from architecture, engineering, biology, and agronomy to find new and innovative approaches for management of local water cycles (Oral et al., 2021). The treatment of greywater has recently gained attention, though the topic remains scarcely addressed in research (Santos et al., 2024). Studies have yielded good results for conventional pollutants, but micropollutants – such as PPCPs – and pathogen removal have been addressed in only a few instances. Despite the limited research, this is a new application of TWs projected to grow significantly in the coming years. For example, the government in Chile – the country with the highest water stress in LAC – has actively promoted the use of TWs for greywater treatment and reuse. A unique large-scale TW is also in operation in Oman treating oily produced water (Stefanakis et al., 2018) with a capacity of 175,000 m³/day and covering an area of 490 hectares. The treated effluent is reused for the irrigation of commercial crops (e.g. biofuels) and the reed biomass is used to produce compost, demonstrating at industrial scale the potential to close the loop of water and resources.

Case studies

A recent case study demonstrates the potential to implement TW at large-scale. This TW has been built in Saudi Arabia for the Red Sea project with a design capacity of 16,000 m³/day, corresponding to up to 80,000 inhabitants (Figure 1.16; Ishtiaq et al., 2025) and the largest TW worldwide for municipal wastewater management. The challenge for this system was not only its size but also the environmental conditions in the area, i.e. a desert environment with high temperatures that could result in high water losses through evapotranspiration. The treatment train includes a pre-treatment stage (screening, sand and fat removal) followed by two-stage vertical flow TW and an HF horizontal flow TW. Effluent recirculation and wastewater step-feeding is applied to enhance total nitrogen removal. Local reed species (*Phragmites communis*, syn. *australis* and *Cyperus papyrus*) have been planted. The first two operational years demonstrated the high treatment efficiency as the effluent quality complied with the strict national standard and is reused for landscape irrigation.



Figure 1.16: The large-scale TW in Saudi Arabia treating 16,000 m³/day of municipal wastewater (Ishtiaq et al., 2025).

Another interesting case study is in Lima, Peru. A TW was designed and constructed with an area of 25,000 m² consisting of six HSSF TW cells (Figure 1.17; Turcios et al., 2021). The system treats domestic and industrial effluents, providing an effluent quality appropriate for reuse in irrigation. The beds are planted with native plant species: Achira (*Canna indica*) and Paragüitas (*Cyperus alternifolius*).



Figure 1.17: TW cells with Achira (Canna edulis) (above), and Paragüitas (Cyperus alternifolius). (Photo: Rosa Miglio) in Peru.

Recommendations

TW have been extensively studied and implemented primarily in developed countries. However, regions such as Latin America and the Caribbean, Africa, and Middle East still show low levels of research and adoption. This disparity is critical because, due to their limited financial resources, TW technology is more crucial than ever in these regions. Its wider implementation would directly contribute to reducing water source pollution and protecting human health, which are essential steps toward ensuring long-term water security. Greater collaboration between developed-country researchers and their low-income region counterparts must be encouraged. Additionally, the study of micropollutants (such as PPCPs, MPs, and PFAS) in TW needs deepening, especially through long-term studies to fully understand the ultimate fate of these pollutants and their impact on the system's efficiency for removing conventional pollutants.

Conclusions

The status of TW technology has now demonstrated not only its high treatment capacity but also its multifunctional nature that can provide a wide range of ecosystem services and functions while representing one of the most cost-effective and acceptable solutions in the water sector. The existing case studies and full-scale applications, as well as the continuous and increased research output place TW technology to the forefront of the transition to a resilient water sector. Our SG is a unique international group on TW and NBS that gathers the top global experts on this technology, covering practically the whole diversity and range of applications. Through our members, we have the capacity to communicate the state-of-the-art of this nature-based technology and support further the expansion and development to new areas.

References

Addo-Bankas, O., Zhao, Y., Wei, T., and Stefanakis, A. (2024). From past to present: Tracing the evolution of treatment wetlands and prospects ahead. *Journal of Water Process Engineering* 60, 105151.

Avellán T., Gremillion P. (2019) Constructed wetlands for resource recovery in developing countries. *Renewable and Sustainable Energy Reviews* 99, 42–57.

Bafrani, A.J., Mirbagheri, S.A., Shafiepour, E., Kinsley, C., Stefanakis, A. (2024). Investigating the effect of hydraulic residence time, artificial aeration and plants presence on different constructed wetland designs treating oil industry effluent. *Journal of Environmental Management* 370, 122348. https://doi.org/10.1016/j.jenvman.2024.122348

Chen Z., Chen Y., Vymazal J., Kule L., Kozeluh M. (2017) Dynamics of chloroacetanilide herbicides in various types of mesocosm wetlands. *Science of the Total Environment* 577, 386–394.

Gholipour A., Zahabi H., Stefanakis A.I. (2020) A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment. *Chemosphere* 247, 125966.

Hou, Y., Ren, B., Li, X., Buque, A. L., and Zhao, Y. (2025). Constructed wetlands for emerging pollutants removal: a decade of advances and future directions (2014–2024). *Journal of Water Process Engineering* 69, 106533.

Ishtiaq, M., Akram, M., Tao, S., Belmaati, H., Siyech, M.H., Sievert, W., Stefanakis, A. (2025). Two years monitoring and optimization of a large-scale constructed wetland in the Red Sea designed for 80,000 inhabitants. *Journal of Cleaner Production* 501, 145307. https://doi.org/10.1016/j.jclepro.2025.145307.

Larsen, J.D., Marieke ten, H., Nielsen, S., (2018). Life cycle assessment comparing the treatment of surplus activated sludge in a sludge treatment reed bed system with mechanical treatment on centrifuge. *Journal of Cleaner Production*, 185, 148–156. DOI: 10.1016/j.jclepro.2018.02.193

Li, M., Zhao, X., Yan, P., Xie, H., Zhang, J., Wu, S., and Wu, H. (2024). A review of per-and polyfluoroalkyl substances (PFASs) removal in constructed wetlands: Mechanisms, enhancing strategies and environmental risks. *Environmental Research*, 262, 119967.

Lv T., Carvalho P.N., Zhang L., Zhang Y., Button M., Arias C.A., Weber K.P., Brix H. (2017) Functionality of microbial communities in constructed wetlands used for pesticide remediation: Influence of system design and sampling strategy. *Water Research* 110, 241–251.

Masi F., Rizzo A., Regelsberger M. (2018) The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. *Journal of Environmental Management* 216, 275–284.

Matamoros V., Rodríguez Y., Bayona J.M. (2017) Mitigation of emerging contaminants by full-scale horizontal flow constructed wetlands fed with secondary treated wastewater. *Ecological Engineering* 99, 222–227.

Montoya, A., Tejeda, A., Sulbarán-Rangel, B., and Zurita, F. (2023) Treatment of tequila vinasse mixed with domestic wastewater in two types of constructed wetlands. *Water Science & Technology*, 87(12), 3072–3082.

Mozaffari, M.H., Shafiepour, E., Mirbagheri, S.A., Rakhshandehroo, G., Wallace, S., Stefanakis, A.I. (2021) Hydraulic characterization and removal of metals and nutrients in an aerated horizontal subsurface flow "racetrack" wetland treating oil industry effluent. *Water Research* 200, 117220. https://doi.org/10.1016/j.watres.2021.117220

Muduli, M., Choudharya, M., Ray, S. (2024) A review on constructed wetlands for environmental and emerging contaminants removal from wastewater: traditional and recent developments. *Environment, Development and Sustainability*, 26(12), 30181–30220.

Nielsen, S., Stefanakis, A. I. (2020) Sustainable dewatering of industrial sludges in sludge treatment reed beds: experiences from pilot and full-scale studies under different climates. *Applied Sciences* 10(21), 7446. https://doi.org/10.3390/app10217446

Nivala, J., Murphy, C., Freeman, A. (2020) Recent advances in the application, design, and operations and maintenance of aerated treatment wetlands. *Water* 12(4), 1188. https://doi.org/10.3390/w12041188.

Oral, H.V., Radinja, M., Rizzo, A., Kearney, K., Andersen, T.R., Krzeminski, P., Buttiglieri, G., Ayral-Cinar, D., Comas, J., Gajewska, M., et al. (2021) Management of urban waters with nature-based solutions in circular cities—exemplified through seven urban circularity challenges. *Water*, 13, 3334.

Santos, J., Rodrigues, S., Magalhães, M., Rodrigues, K., Pereira, L., Marinho, G. (2024). A state-of-the-art review (2019–2023) on constructed wetlands for greywater treatment and reuse. *Environmental Challenges*, 16, 100973.

Savvidou, P., Dotro, G., Campo, P., Coulon, F., Lyu, T. (2024) Constructed wetlands as nature-based solutions in managing per-and poly-fluoroalkyl substances (PFAS): Evidence, mechanisms, and modelling. *Science of the Total Environment*, 934, 173237. https://doi.org/10.1016/j.scitotenv.2024.173237

Šereš, M., Innemanová, P., Hnátková, T., Rozkošný, M., Stefanakis, A.I., Semerád, J., Cajthaml, T., (2021). Evaluation of hybrid constructed wetland performance and reuse of treated wastewater in agricultural irrigation. *Water* 13(9), 1165, https://doi.org/10.3390/w13091165.

Stefanakis, A.I., Akratos, C.S., Tsihrintzis, V.A., 2014. *Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment*, first ed. Elsevier Publishing. https://doi.org/10.1016/C2012-0-01288-4

Stefanakis A.I., Prigent S., Breuer R. (2018) Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: *Constructed wetlands for industrial wastewater treatment*. Stefanakis A.I., (ed. John Wiley & Sons Ltd., pp. 25–42).

Tatoulis, T., Akratos, C.S., Tekerlekopoulou, A., Vayenas, D.V., Stefanakis, A.I. (2017) A novel horizontal subsurface flow constructed wetland: Reducing area requirements and clogging risk. *Chemosphere*, 186, 257–268. https://doi.org/10.1016/j.chemosphere.2017.07.151.

Tondera K., Ruppelt J., Pinnekamp J., Kistemann T., Schreiber C. (2019) Reduction of micropollutants and bacteria in a constructed wetland for combined sewer overflow treatment after 7 and 10 years of operation. *Science of the Total Environment* 651, 917–927.

Turcios, A.E., Miglio, R., Vela, R., Sánchez, G., Bergier, T., Włodyka-Bergier, A., Cifuentes, J.I., Pignataro, G., Avellan, T., Papenbrock, J., (2021) From natural habitats to successful application - Role of halophytes in the treatment of saline wastewater in constructed wetlands with a focus on Latin America. *Environmental and Experimental Botany*, 190, 104583. https://doi.org/10.1016/j.envexpbot.2021.104583

Wang, Q., Li, Y., Yang, X., Van Hulle, S. W., & Rousseau, D. P. (2024) Microplastics in two different constructed wetlands systems for wastewater treatment: Removal and fate. *Journal of Environmental Chemical Engineering* 12(6), 114341.

Zamora-Castro, S. A., Orduña, M. G. H. y., Moreno-Seceña, J. C., Martínez Escalante, G. A., Sangabriel Lomeli, J., Zitácuaro-Contreras, I., & Marín-Muñiz, J. L. (2025) Maximizing value in constructed wetlands: A review of ornamental plants for wastewater treatment and artisanal applications. *Earth* 6(4), 126. https://doi.org/10.3390/earth6040126

Zhuang L-L, Li, M., Li, Y., Zhang, L., Xu, X., Wu, H., Liang, S., Su, C., Zhang, J. (2022). The performance and mechanism of biochar-enhanced constructed wetland for wastewater treatment. *Journal of Water Process Engineering* 45, 102522. https://doi.org/10.1016/j.jwpe.2021.102522



| 2 |

Digital water and innovation

| 2.1 |

Full-scale digital twins for water resource recovery facilities and beyond

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Introduction

In recent years, the water sector has undergone significant digital development. Enhanced data availability, coupled with advances in computational power, has shifted model applications toward real-time decision-making, particularly through the development of digital twins. A digital twin (DT) can be seen as a combination of models with an automated, live data connection to the real physical system (Torfs et al., 2022). As such, DTs support a transition towards proactive management by making data connected and actionable in real-time for system understanding and optimisation. In recent years DTs have progressed from research concepts and visionary prototypes to fully operational, real-time decision support systems. In this contribution, the Modelling and Integrated Assessment (MIA) Specialist Group highlights the latest advancements in digital twin development and their growing role in water resource recovery facilities (WRRFs).

DTs are now promising candidates for supporting a wide range of operational, planning, and optimisation needs. By combining mechanistic models, data-driven components, soft sensors, and real-time data streams, they provide utilities with enhanced insight into system behaviour, improved forecasting capability, and more robust process control. Their applications span monitoring, scenario analysis, optimisation of energy and chemicals use, operator decision support, and real-time control. This contribution starts by presenting three case studies of fully implemented DTs, offering a snapshot of where the sector currently stands on the adoption curve. It then explores the emerging potential of DTs for advanced, intelligent plant-wide control, leveraging model-based approaches and reinforcement learning. Finally, key needs and challenges associated with scaling digital twins beyond individual facilities are addressed, envisioning a truly connected water sector supported by holistic, DT-based decision support tools – a significant opportunity shaping the near future of the field.

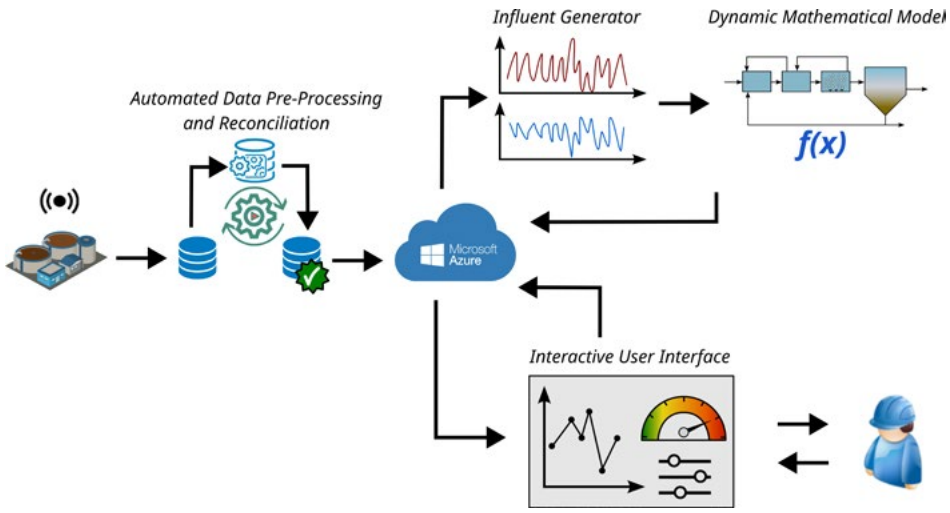


Figure 2.1: Overview of the Eindhoven DT main components and their connections (Daneshgar et al., 2024)

Plant-wide case studies of digital twins of water resource recovery facilities

Case study 1: Digital twin for operational decision support for the Eindhoven WRRF

DESCRIPTION AND OBJECTIVES

This case study presents the digital twin (DT) for the Eindhoven WRRF in the Netherlands. The Eindhoven DT, at its core (Figure 2.1), integrates an open-source automated data- pipeline, a deterministic influent generator for forecasting, a plant-wide model and a user-centered interface. Co-creation with plant staff ensured that human factors and operational needs shaped the tool's functionality and relevance.

The DT enables continuous monitoring of the plant, supports scenario-based analyses on both historical and forecasted conditions, and allows users to test operational strategies or future controller upgrades before implementation. This facilitates proactive, informed and cost-effective plant management.

DATA PIPELINE

The Eindhoven WRRF relies on extensive online sensor data collected through a supervisory control and data acquisition (SCADA) system and stored in an iHistorian database. A continuous (every 2 hours) and automated data pipeline was developed to ensure transparent and validated data for the Eindhoven DT.

The pipeline is implemented through two Python packages (Figure 2.2):

1. *wwdata* (De Mulder et al., 2018) provides core preprocessing tools, including detection of missing, extreme, or faulty sensor signals; smoothing filters; and multiple gap-filling methods. (Repository: https://github.com/UGentBiomath/wwdata)
2. *wwtwin* (Daneshgar et al., 2024a) automates the end-to-end pipeline from data extraction to model simulation (Repository: https://github.com/UGentBiomath/wwtwin)

DIGITAL TWIN MODELS AND TOOLS

An empirical influent generator (Langeveld et al., 2017) reproduces influent dynamics under varying hydrological conditions for non-measured water quality variables (total suspended solids, TSS; chemical oxygen demand, COD; ammonium; phosphate). In hindcast and real-time modes, validated influent flow data from the *wwtwin* pipeline are combined with concentrations predicted by the influent generator. For forecasting, the influent generator predicts flow and concentration dynamics via an extended rainfall-runoff model (Meirlaen et al., 2001).

The core of the DT is a dynamic plant-wide model of the Eindhoven WRRF developed in the WEST© simulation environment (DHI, Denmark) and using a modified ASM2d framework for chemical and biological phosphorus removal (Amerlinck, 2015). Non-ideal mixing in the full-scale plant, identified through computational fluid dynamics-biokinetics studies (Rehman, 2016), necessitated the development of a compartmental model for the aeration tank (De Mulder, 2019) – enhancing dissolved oxygen (DO) and air-flow predictions – as well as the anoxic tank - reflecting observed stratification patterns caused by return activated sludge (RAS) flow from the secondary clarifier (Borzooei et al., 2023).

DHI's TwinPlant© technology integrates the Eindhoven WRRF's continuous data-processing pipeline and plant-wide model into a single operational interface, enabling operators and process engineers to monitor real-time performance, view process indicators and key performance indicators (KPIs), and access 48-hour predictive simulations. Users can explore what-if scenarios in both historical and forecast modes by adjusting operational settings, controller parameters, or input time series, supporting proactive decision-making and testing of future strategies. The interface also features

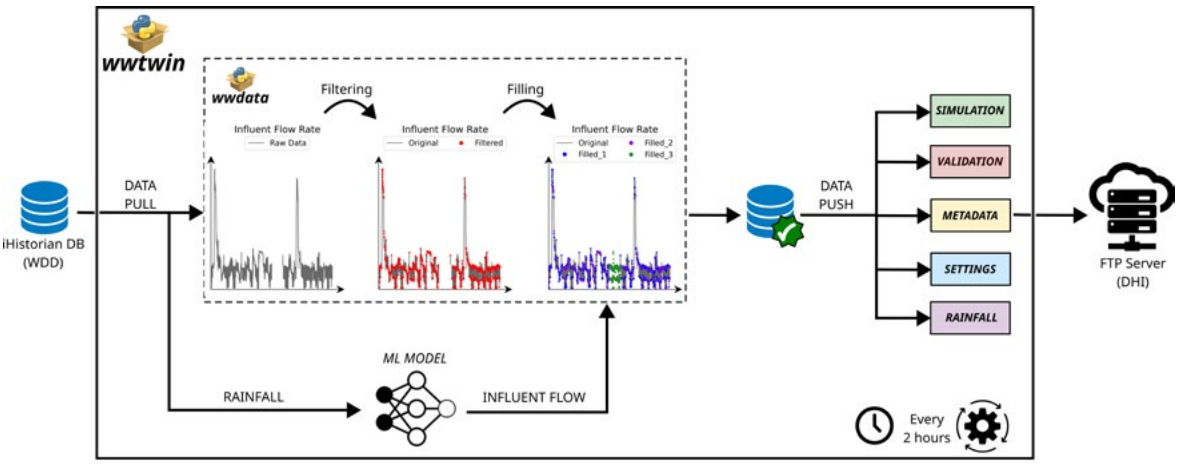


Figure 2.2: Overview of the data pipeline for the Eindhoven DT (Daneshgar et al., 2024b)

automated multivariate anomaly detection using dynamic principal component analysis (PCA) and isolation forests algorithms, providing early identification of sensor or process irregularities. Together, these tools offer a comprehensive, user-centred environment for monitoring, optimisation, and operator training.

OPERATOR INVOLVEMENT (PATH TO TRUST)

The Eindhoven DT development placed strong emphasis on the "human factor", recognising that its long-term success depends on daily use by WDD operators and process engineers. The development team held regular workshops and feedback sessions over nearly two years, engaging staff with varying levels of digital expertise in hands-on testing and iterative refinement. These interactions guided key design choices including selection of meaningful KPIs, and operational scenarios and identifying essential control handles.

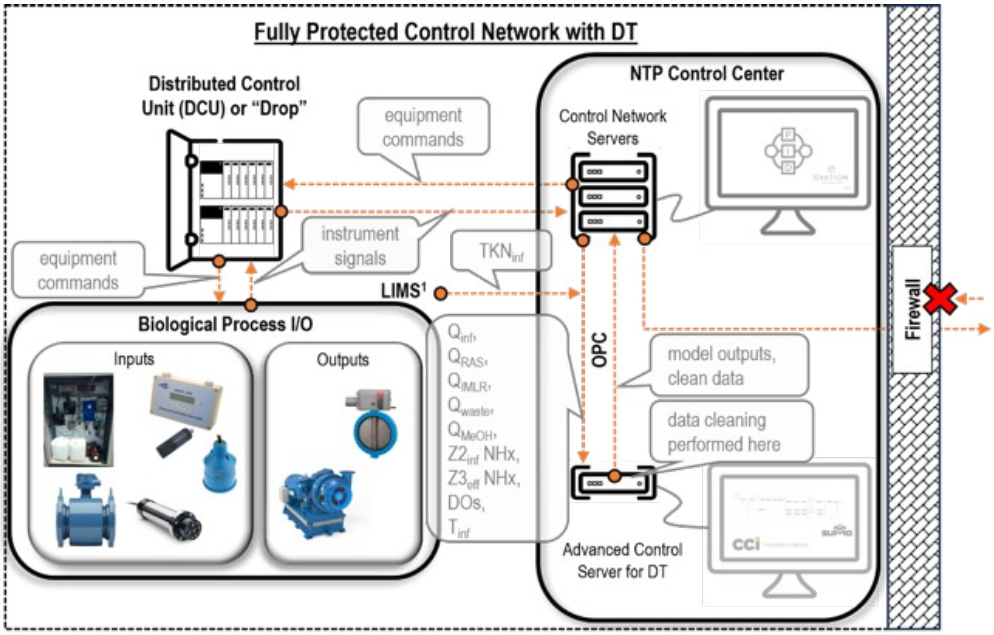


Figure 2.3: Overview of the main NTP digital twin components and their connections.

FUTURE VISION

The Eindhoven DT has been operating for nearly two years, providing real-time simulations and 48-hour forecasts. Its development is ongoing, with continuous extensions to the plant-wide model (e.g. including N_2O emissions, improving settling model). To maintain long-term reliability, an automated recalibration framework using evolutionary neural networks is being incorporated into the real-time simulation platform (Gomez et al., 2025). Finally, the DT is already supporting semi-automated process optimisation by recommending optimal aeration set-points for multiple objectives, establishing a human-in-the-loop link between the virtual and physical plant and paving the way toward more advanced automated operational optimisation in future releases.

Case study 2: Digital twin for ammonia control at the HRSD Nansemond Treatment Plant

DESCRIPTION AND OBJECTIVES

The following case study presents the full-scale implementation of a hybrid DT used to support advanced ammonia control at the Nansemond Treatment Plant (NTP) of the Hampton Roads Sanitation District (HRSD), in Eastern Virginia, USA (Figure 2.3). Details can be found in Sparks (2024).

The NTP, designed for approximately 115,000 m³/d (30 MGD), operates a five-stage Bardenpho process for biological nutrient removal.

Its primary objectives are to minimise aeration energy use while meeting strict total inorganic nitrogen (TIN) limits (< 5 mg/L N) required for indirect potable reuse (IPR), to maintain a small positive ammonia (NHx) residual entering chlorination to favour chloramine formation and reduce sodium hypochlorite consumption, and to equip operators with guidance on sludge wasting that helps prevent control authority loss and optimise solids retention time (SRT) across varying loads and seasonal temperatures.

DATA PIPELINE

The NTP DT integrates near real-time data from the Emerson Ovation Distributed Control System via open platform communications to/from a local, dedicated, and air-gapped server for cybersecurity. Laboratory results are entered daily from the laboratory information management system (LIMS).

Data reliability is preserved through built-in fault detection and gap-filling routines inside a Python-based analytics engine known as CCI Cake (Control Consulting Inc., Bellingham, WA USA), which maintain forecasting continuity even during sensor faults. These routines include automated screening of incoming data for out-of-range values, rate-of-change violations, sensor flat-lining, and significantly high univariate time series model forecast errors. The DT substitutes short-term faults with those forecasts or uses validated fall-back soft sensors to bridge extended periods of unreliable data. This prevents propagation of erroneous measurements into the simulation and ensures that controller inputs remain stable and trustworthy during temporary data quality issues.

DIGITAL TWIN MODELS AND TOOLS

Running in the Sumo© software by Dynamita (Sigale, France), the DT simulates the plant's liquid train, including primary clarifiers, biological process, and secondary clarifiers, with a one-minute time step (Sparks et al., 2025).

The DT's core mechanistic model, based on Activated Sludge Model No. 1 (ASM1), is calibrated to full-scale operating data and includes an automated optimisation routine that soft-senses the maximum nitrifier specific growth rate (µmax-NITO) twice per week. To maintain appropriate nitrifier populations and consistent performance, the DT executes scenario analyses involving 1,000 simulations per half-week cycle, evaluating how waste rates, temperature forecasts, and influent loads influence control authority and recommending optimal waste-rate ad-justments accordingly.

OPERATOR INVOLVEMENT (PATH TO TRUST)

Operators were not directly involved in developing the Digital Twin, as the DT was designed primarily as an engineering-level tool for process analysis, soft-sensing, and advanced control applications. For operators, the deployment was intentionally framed not as a new technology that they needed to build or maintain, but as a new controller integrated within their existing control environment.

The control system allows operators to toggle the DT-assisted controller on or off at any time, while built-in interlocks automatically revert operation to the simpler legacy ammonia-based aeration control (ABAC) PI loop if NHx levels exceed defined limits or if data quality deteriorates. The DT's recommendations are displayed directly within the existing control system graphics, maintaining the same look and feel as hard sensor feedback and standard PI controller outputs.

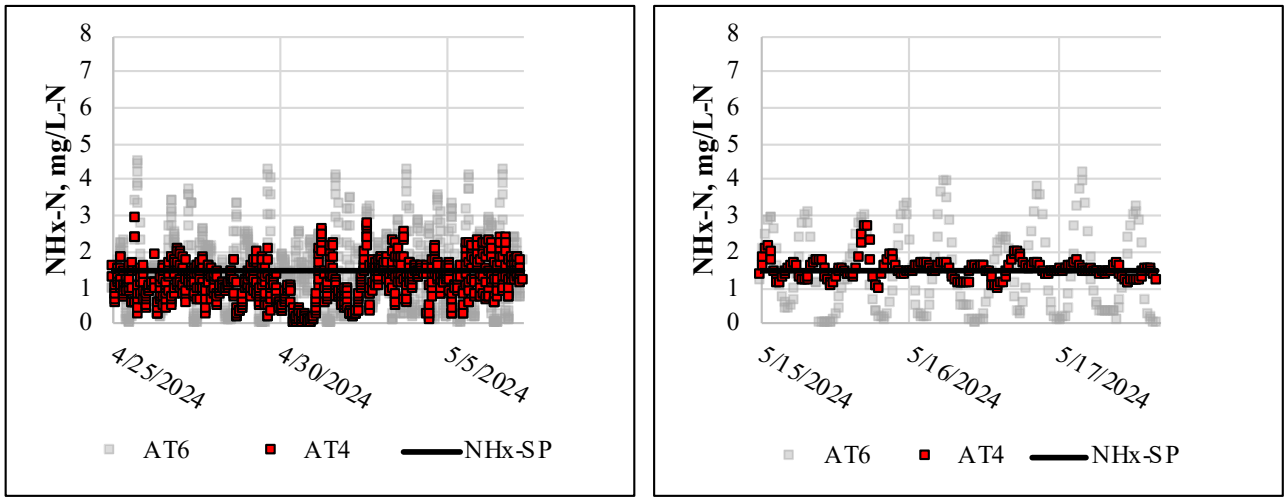


Figure 2.4: (a) Hybrid controller performance (red, NTP lane 4) compared to the baseline controller (grey, NTP lane 6) before tuning associated feedback controllers. The NHx setpoint is shown in black, AT stands for aeration tank. (b) Hybrid controller performance (red) compared to the baseline controller performance (grey) after tuning associated feedback controllers. The NHx setpoint is shown in black.

The DT also includes data-driven models in a parallel hybrid architecture, combining mechanis-tic modelling with machine learning corrections, where the machine learning models forecast the mechanistic model NHx errors. When deployed to govern DO setpoints for maintaining a steady effluent NHx concentration, the hybrid controller achieved more than a 90% reduction in the controller mean squared error compared with the baseline proportional integral (PI) controller, demonstrating a marked improvement in stability and accuracy (Figure 2.4).

A dashboard displays the DT's µmax-NITO trends, waste-rate scenarios, and time series charts that reflect data-driven model performance, enabling staff to review system performance and respond appropriately.

FUTURE VISION

Building on the success of the NTP deployment, HRSD is busy expanding DT and hybrid con-trol systems across its treatment network. The next phase will support mainstream partial deni-trification anammox (PdNA) processes that require tight ammonia versus NOx (AvN) ratio control, as well as deeper integration with IPR operations to guarantee uninterrupted aquifer recharge. The DT framework will also underpin operator training, scenario-based learning, and fault detection through comparison of hard and soft sensor outputs.

Case study 3: Digital twins for reducing capital costs in design

DESCRIPTION AND OBJECTIVES

The majority of DT applications currently emphasise optimising day-to-day operations – leveraging live data streams and integrated modelling for real-time decision support. Their use in the planning and design phase remains largely under-explored. This represents a missed opportunity, as the design phase is a critical period where key technical and financial decisions are made.

This case study examines the concept of DT applications in the design phase for full-scale WRRFs, to demonstrate the financial benefits of reducing design uncertainty. The two full-scale examples are:

1. **Marine Park WWTF (City of Vancouver, WA, USA):** improving existing aeration basin performance with advanced aeration control and mixed liquor recirculation to address increasing influent loads and sludge popping issues in the clarifiers.
2. **Davyhulme wastewater treatment works (WWTW) (Greater Manchester, UK):** generating a long-term influent dynamic profile that can be used by the design teams to minimise conservatisms and costs for a number of planned expansion projects across the liquid streams.

DATA PIPELINE

Historical data were collected, processed, and consolidated from both SCADA and LIMS ensuring comprehensive coverage of operational and laboratory data. Simple univariate data cleaning procedures were applied sequentially, including resampling, outlier removal using both manual bounds and the interquartile range (IQR) method, followed by linear interpolation for imputation and lastly smoothing.

DIGITAL TWIN MODELS AND TOOLS

Johnson et al. (2024) developed a set of DT tools that integrate mechanistic modelling with machine learning to address the challenge of limited high-resolution data availability. Among these tools, the soft sensor module (see Figure 2.5), stands out for its ability to leverage existing historical data – aeration profiles, flow rates, and laboratory measurements – to generate useful, detailed, dynamic influent loading profiles, not just statistical estimation. Moreover, the soft sensor also provides additional valuable design insights – such as the alpha factor and biokinetic parameters of the system – which are typically expensive to measure in situ but highly useful for informing process mechanistic design. This enables more informed decision-making during the design and operation phases, supported by richer and more dynamic datasets. Historical data were fed into the DT-based soft sensor to generate the 15-min dynamic influent profiles along with biological kinetics, stoichiometry, and fractionation. Technical details about the soft sensor implementation can be found in Cheng et al. (2023) and Johnson et al. (2024).

Figure 2.6 illustrates a comparison between dynamic signals from the soft sensor and physical sensors for the Davyhulme WWTW, showing that the temporal patterns – including the magnitude, timing of peaks and valleys, and the rate of change (slopes and inclines) – are closely aligned between the soft sensor estimates and the measured values. Notably, none of the physical sensor data was fed into the soft sensor, therefore, the agreement between the soft sensor and physical measurements reflects an independent validation.

The soft sensor data are then used in the two design efforts, leading to significant capital cost savings at the two facilities:

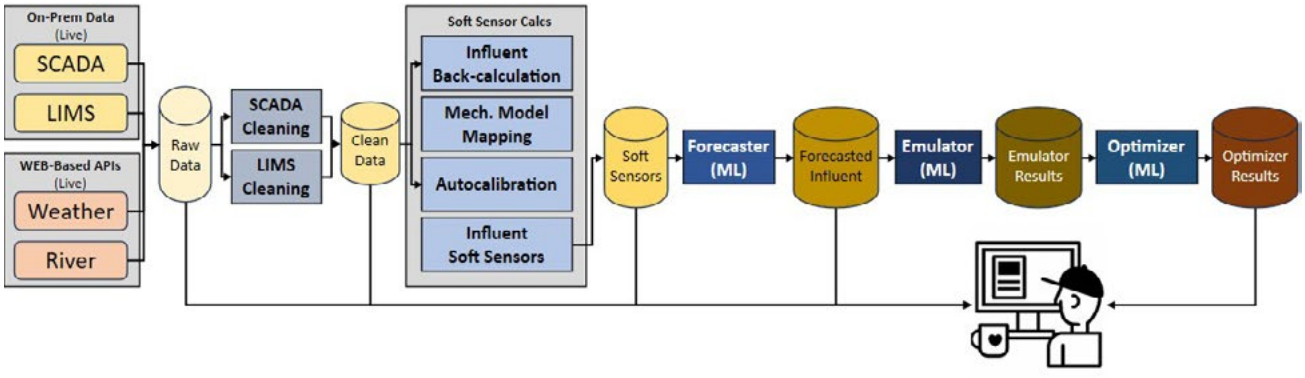


Figure 2.5: Overview of the DT soft sensor main components and their connections

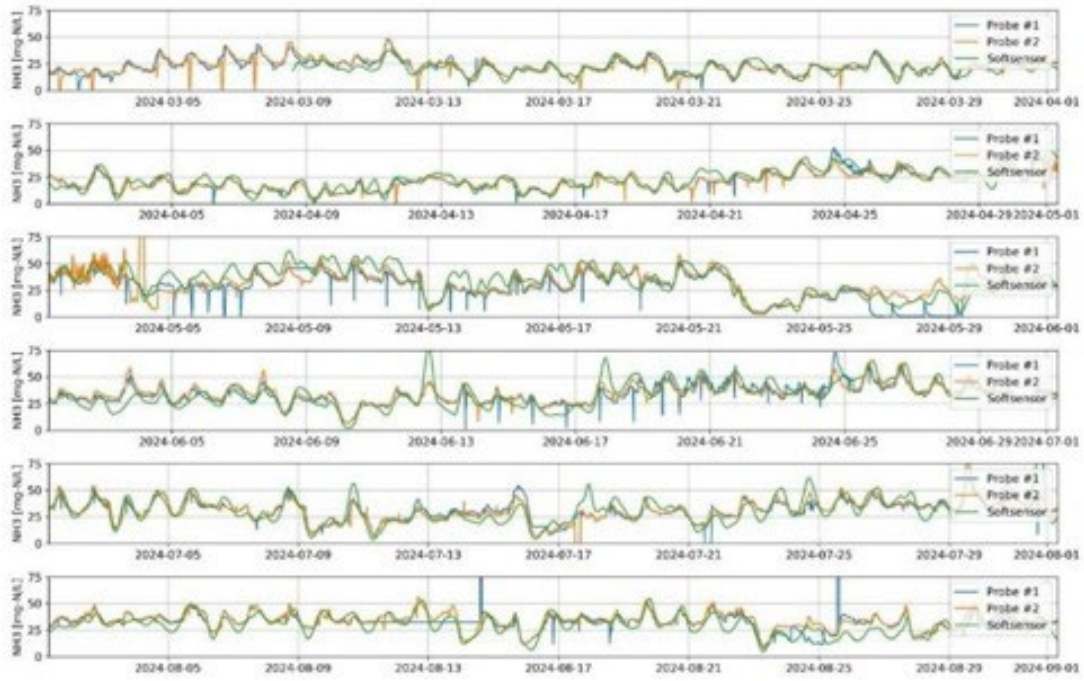


Figure 2.6: Davyhulme WWTW soft sensor versus ion selective probe primary effluent ammonia comparison

1. **Marine Park WWTF:** The capital project cost estimate was reduced from USD$13 million to approximately USD$5 million with a large portion of the savings a direct result of the DT for design work.
2. **Davyhulme WWTW:** The DT for design showed that one of the existing bioreactor systems had the capacity to manage a doubling of the side stream ammonia loads with only minor control system upgrades. This approach eliminated the expense of adding a new nitrogen treatment system with an estimated capital cost of greater than £30 million.

FUTURE VISION

A key outcome of both case studies was the identification of lower-cost design solutions that could achieve desired performance outcomes without the need for major infrastructure expansion. This illustrates the increasing relevance of DTs in modern process design. As the technology continues to evolve and as utilities and design teams gain experience with its implementation, digital twins are expected to become an integral part of future design practices – supporting more informed, efficient, and resilient infrastructure development.

Challenges in bringing digital twins to practice

Whereas successful implementation of a DT relies on many different steps, in practice, the larger hurdles often arise from data and purpose.

Establishing a robust and secure data pipeline from SCADA and laboratory systems to the cloud requires early planning, careful design choices, and close collaboration between IT and operations, particularly given the significant cybersecurity constraints involved. Even when data is available, inconsistent naming and incomplete metadata can severely limit usability, making a unified data model essential. In parallel, rigorous and automated data cleaning and imputation are critical to ensure reliable model performance at scale. The model is also only as good as its inputs, which places strong emphasis on robust influent characterisation, whether through (soft) sensing or influent generators. Coupled to this rigorous data pipeline, DTs must remain adaptive: continuous performance monitoring and strategies for automatic recalibration are needed, so deviations trigger either model updates or targeted analysis.

Ultimately, however, the decisive barrier is organisational: DTs only succeed when their value is clearly defined, measurable, and aligned with stakeholder needs – otherwise they risk becoming technically impressive, but operationally irrelevant, prototypes.

Digital twin-based plant-wide control

Model-based control in the digital water transition

The above DT case studies demonstrate that DTs provide real-time synchronisation between mechanistic models, soft sensors, and plant data, enabling predictive optimisation of operational costs, effluent quality, and reliability. Within this context, DT-supported model predictive control (MPC) is increasingly applied in wastewater treatment plants (WWTPs) as it enables proactive management of influent variability, aeration, and multi-objective trade-offs between effluent quality and energy use. A particularly notable example is the work of Stentoft et al. (2019, 2021) where stochastic electricity markets are implemented in an MPC algorithm, allowing WWTPs to co-optimise treatment performance and energy costs under uncertainty.

As MPC must solve a constrained nonlinear optimisation problem at each control timestep, plant-wide, real-time MPC is computationally demanding, especially for complex full-plant models with 50+ state variables, and nonlinear biological kinetics acting over different temporal scales. Reduced order (Stentoft et al., 2019) or data-driven surrogate models (Bernadelli et al., 2020) are often required to keep computations feasible. Reinforcement learning (RL), a branch of artificial intelligence where agents learn optimal control policies by interacting with their environment, offers new opportunities for real-time, holistic control (Sutton and Barto, 2018). Unlike traditional PI/PID loops or MPC, RL agents learn control strategies through direct interaction with the control environment. By leveraging DTs as safe training environments, RL can learn adaptive control policies without explicit reliance on detailed process models, offering a scalable path toward plant-wide optimisation.

RL research in wastewater treatment has progressed in recent years from early DO setpoint optimisation to comprehensive plant-wide control. Foundational work by Hernández-del-Olmo et al. (2012) using Q-learning on standardised environments such as the Benchmark Simulation Model No. 1 (BSM1, Gernaey et al., 2014) achieved modest operational improvements. Modern continuous action methods, including actor-critic architectures, deep deterministic policy gradient (DDPG), and proximal policy optimisation (PPO), now control multiple actuators simultaneously, demonstrating 5–15% aeration energy reductions and 8–12% facility-wide cost reductions while maintaining effluent compliance (Croll et al., 2024; Wang et al., 2024a, 2024b). Multi-agent approaches extend these capabilities across entire treatment trains (Chen et al., 2021).

While the majority of work has been limited to simulation or bench- and pilot-level deployment, demonstration-level deployment to full-scale membrane bioreactors reports 30–33% aeration energy savings (Nam et al., 2020, 2023). These demonstrations establish RL as a credible pathway for system-wide optimisation, complementing or replacing conventional control tools.

CHALLENGES PREVENTING LARGE-SCALE DEPLOYMENT OF RL CONTROL

Despite promising results, the majority of work has been limited to simulation or bench- and pilot-level deployment as widespread operational deployment of RL control faces methodological, and safety-related barriers. RL training requires hundreds of thousands to millions of interactions, feasible only with high-fidelity DTs, yet simulations seldom capture rare events like equipment failures or extreme weather. Distribution shifts between simulated and real conditions degrade policy reliability, requiring frameworks to quantify uncertainty before deployment.

Water utilities operate under strict regulatory and safety constraints requiring transparent, auditable control decisions. Explainable AI methods, including contrastive explanations and counterfactual analyses, are advancing transparency but require broader institutionalisation across the sector (Gomez, 2026).

Additionally, temporal credit assignment, determining which actions contributed to which outcomes, represents a fundamental and challenging difference between water systems and domains like robotics, where RL has matured rapidly. Biological wastewater treatment exhibits cascading dynamics where DO reductions initiate responses unfolding over 2–4 hours (denitrification), 6–10 hours (nitrification impairment), and 12–24 hours (effluent violations), and changes to solids wasting rates might initiate responses as much as a week into the future, creating substantial delays between actions and observable consequences (Henze et al., 2000). Standard RL algorithms struggle with delayed feedback as reward signals arrive long after critical decisions.

PATH FORWARD: ENABLING TRUSTWORTHY RL DEPLOYMENT

Next-generation RL controllers are moving toward specialised architectures designed for multi-timescale processes. Continuous-time neural networks with learnable time constants offer advantages over traditional recurrent networks (LSTMs, RNNs) because they represent dynamical systems through differential equations with input-dependent temporal processing speeds rather than assuming fixed sampling intervals (Hasani et al., 2021; Gomez, 2026). This supports the implementation of reward redistribution methods that systematically attribute delayed outcomes to causal actions. Moreover, these temporal-aware architectures offer more interpret-able, process-aligned parameters that operators can relate to known biological and hydraulic timescales. Operators benefit from explanations framed operationally: “aeration was reduced because ammonia was stable while energy costs increased”, rather than generic feature importance scores.

A realistic adoption pathway includes offline evaluation using historical data; advisory mode where RL provides recommendations while humans retain control; supervised autonomous op-eration with operator veto capabilities; and eventually full autonomy with embedded safeguards. This gradual approach allows utilities to build confidence while continuously validating per-formance across operating conditions.

Scale-up and interoperability for system-level digital twins

The presented case studies show that DTs can significantly improve system operation and design. While most current implementations focus on single plants, the next step is scaling up – linking multiple facilities, integrating sewer networks with WRRFs and combining centralised and decentralised systems towards fully integrated urban wastewater system (IUWS) DTs.

Achieving system-wide DT integration requires advances in both technology and stakeholder alignment, with data management emerging as a fundamental enabler and barrier (Ghorbani Bam et al., 2025). A key challenge persists to integrate large and scattered amounts of information in a way that it becomes accessible, interoperable and actionable. As DTs scale, data becomes increasingly fragmented across platforms: operational data (historian/SCADA), maintenance records (CMMS), laboratory data (LIMS); financial systems (SAP); and consumption or customer information systems. This fragmentation makes data governance, standardisation, and security critical.

The sewer–WRRF interface illustrates this particularly well. Integrating sewer networks and treatment plants within a single DT can enable early-warning alerts for abnormal discharges, improved understanding of system responses to weather events or shifts in water use (Lumley et al., 2024). While WRRF data systems are relatively mature, sewer data – especially water quality – are often sparse and unreliable. Sensors are deployed in harsh environments leading to intermittent data streams that limit DT capabilities.

These challenges become even more pronounced in developing countries where sewered and onsite sanitation coexist. In many cities, non-sewered systems are widely used but are not yet “DT-ready”. Nevertheless, they remain an essential part of the urban water framework and must be included in long-term digital integration strategies. Emerging work on soft sensors, probabilistic models, and data-light DT approaches may help bridge this gap, but this remains an underexplored research area (Ward et al., 2021).

Recent efforts highlight the need for improved interoperability and data frameworks. Solution providers (e.g. Xylem, Bentley, AVEVA) are developing integrated platforms, but adoption across operational levels remains limited. Sustainable DT implementation will require robust data standards and governance frameworks addressing data quality, consistency, accessibility, and long-term usability.

At the same time, research efforts are emerging in the domain of semantic models as an interoperable framework for system level DT development (Akroyd et al., 2021). Semantic modelling uses ontologies and knowledge graphs to define concepts, relationships, and data structures in a standardised way. By enriching data with explicit semantic context, semantic models bridge heterogeneous formats and siloed systems for seamless data integration over different parts of the water sector.

Related fields already demonstrate the value of semantic models. For example, Akroyd et al. (2021) developed a DT to assess public health risk from air pollution around the port of Singapore by using a semantic knowledge graph to integrate heterogeneous data (air quality, weather, geography, demography, and ship activity) with models of combustion and pollutant dispersion. Similarly, Raes et al. (2022) proposed a semantic architecture to orchestrate a large variety of urban data (e.g. air quality, traffic flows, 3D GIS models of urban areas, and noise levels) to create local digital twin for city-scale optimisation. These initiatives provide a blueprint for the water sector, highlighting how semantic modelling can underpin the creation of truly connected DTs that extend beyond single plants to entire networks.

References

Akroyd J, Mosbach S, Bhave A, & Kraft M. (2021). Universal Digital Twin - A dynamic knowledge graph. *Data-Centric Engineering*, 2, e14. doi:10.1017/dce.2021.10

Aponte-Rengifo, O., Vilanova, R., Francisco, M., Vega, P., & Revollar, S. (2023). Optimal set point generation based on deep reinforcement learning and transfer knowledge for Wastewater Treatment Plants. *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*. https://doi.org/10.1109/ETFA54631.2023.10275522

Belfadil, A., Modesto, D., Meseguer, J., Joseph-Duran, B., Saporta, D., & Martin Hernandez, J. A. (2024). Leveraging deep reinforcement learning for water distribution systems with large action spaces and uncertainties: DRL-EPANET for pressure control. *Journal of Water Resources Plan-ning and Management*, 150(2), 04023076.

Bernardelli, A, Marsili-Libelli, S. Manzini, A. Stancari, S., Tardini, G., Montanari, D., Anceschi G., Gelli P., & Venier S. (2020). Real-time model predictive control of a wastewater treatment plant based on machine learning. *Water Science and Technology*, 81 (11), 2391–2400. doi: https://doi.org/10.2166/wst.2020.298

Borzooei S., Daneshgar S., Torfs E., Rehman U., Duchi S., Peeters R., Weijers S., & Nopens I. (2023). Next-generation compartmental models for applications in digital twinning of WRRFs. *8th IWA Water Resource Recovery Modelling Seminar (WRRmod2022+)*, Stellenbosch, South Africa, 18–22 January 2023.

Chen, K., Wang, H., Valverde-Pérez, B., Zhai, S., Vezzaro, L., & Wang, A. (2021). Optimal control towards sustainable wastewater treatment plants based on multi-agent reinforcement learning. *Chemosphere*, 279, 130498. https://doi.org/10.1016/j.chemosphere.2021.130498

Croll, H. C., Ikuma, K., Ong, S. K., & Sarkar, S. (2024). Unified control of diverse actions in a wastewater treatment activated sludge system using reinforcement learning for multi-objective optimisation. *Water Research*, 263, 122179.

Daneshgar, S., Borzooei S., Peeters R., Weijers S., Nopens I., & Torfs E. (2024a). wwtwin: An open-source python package for digital twin applications of WRRFs. *9th IWA Water Resource Recovery Modelling Seminar (WRRmod2024)*, University of Notre Dame, IN, USA, 6–10 April, 2024.

Daneshgar S., Polesel F., Borzooei S., Sorensen H.R., Peeters R., Weijers S., & Nopens I., & Torfs E. (2024b). A full-scale operational digital twin for a water resource recovery facility—A case study of Eindhoven water resource recovery facility. *Water Environment Research*, 96 (3), e11016. http://doi.org/10.1002/wer.11016

De Mulder, C., Flameling, T., Weijers, S., Amerlinck, Y., & Nopens, I. (2018). An open software package for data reconciliation and gap filling in preparation of water and resource recovery facility modeling. *Environmental Modelling and Software*, 107, 186–198. https://doi.org/10.1016/j.envsoft.2018.05.015

Gernaey, K., Jeppsson, U., Vanrolleghem, P. A. & Copp, J. (2014) Benchmarking of Control Strategies for Wastewater Treatment Plants. IWA Scientific and Technical Report No. 23. IWA Publishing, London, UK.

Ghorbani Bam, P., Rezaei, N., Roubanis, A., Austin, D., Austin, E., Tarroja, B., Takacs, I., Villez, K., & Rosso, D. (2025). Digital twin applications in the water sector: A review. *Water*, 17(20), 2957. https://doi.org/10.3390/w17202957

Hajgató, G., Paál, G., & Gyires-Tóth, B. (2020). Deep reinforcement learning for real-time optimisation of pumps in water distribution systems. *Journal of Water Resources Planning and Management*, 146(11), 04020079. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001287

Hasani, R., Lechner, M., Amini, A., Rus, D., & Grosu, R. (2021). Liquid time-constant networks. *AAAI Conference on Artificial Intelligence*, 35(9), 7657–7666. https://doi.org/10.1609/aaai.v35i9.16936

Henze, M., Gujer, W., Mino, T., & van Loosdrecht, M. (2000). *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3*. IWA Publishing, London, UK.

Heo, S., Woo, T., Kim, S., & Yoo, C. (2023). XAI-Assisted multi-agent deep reinforcement learning for a guaranteed autonomous control system of sequencing batch reactor for sustainable wastewater management. *Foundations of Computer Aided Process Operations / Chemical Process Control*.

Hernández-del-Olmo, F., Gaudioso, E., Duro, N., Dormido, R., & Gorrotxategi, M. (2012). Autonomous adaptive and active tuning up of the dissolved oxygen setpoint in a wastewater treatment plant using reinforcement learning. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 42(5), 768–774.

eHu, S., Gao, J., Zhong, D., Wu, R., & Liu, L. (2023). Real-time scheduling of pumps in water distribution systems based on exploration-enhanced deep reinforcement learning. *Systems*, 11(2), 56. https://doi.org/10.3390/systems11020056

Johnson, B., & Townley, L. (2021). *Digital Water Operational Digital Twins in the Urban Water Sector: Case Studies*. www.iwa-network.org

Johnson, B., Yang, C., Lesnik, K., Registe, J., Stewart, H., Rieger, L., Miletic, I., Pienta, D., Xiang, F., Rickermann, J., & Oristian, M. (2024). *Development of Hybrid Digital Twins for Predictive Nutrient Control (Report No. 5121)*. The Water Research Foundation, Denver, CO, USA. https://www.waterrf.org/research/projects/development-hybrid-digital-twins-predictive-nutrient-control

Langeveld, J., Van Daal, P., Schilperoort, R., Nopens, I., Flameling, T., & Weijers, S. (2017). Empirical sewer water quality model for generating influent data for WWTP modelling. *Watermark*, 9, 491. https://doi.org/10.3390/w9070491

Li, X., Wang, D., Zhao, M., & Qiao, J. (2024). Reinforcement learning control with n-step in-formation for wastewater treatment systems. *Engineering Applications of Artificial Intelligence*, 133. https://doi.org/10.1016/j.engappai.2024.108033

Lumley, D. J., Polesel, F., Refstrup Sørensen, H., & Gustafsson, L. G. (2024). Connecting digital twins to control collections systems and water resource recovery facilities: From siloed to inte-grated urban (waste)water management. *Water Practice and Technology*, 19(6), 2267–2278. https://doi.org/10.2166/wpt.2024.128

Meirlaen, J., Huyghebaert, H., Sforzi, F., Benedetti, L., & Vanrolleghem, P. A. (2001). Fast, parallel simulation of the integrated urban wastewater system using mechanistic surrogate models. *Water Science and Technology*, 43(7), 301–309. https://doi.org/10.2166/wst.2001.0439

Nam, K. J., Heo, S. K., Loy-Benitez, J., Ifaei, P., & Yoo, C. K. (2020). An autonomous operational trajectory searching system for an economic and environmental membrane bioreactor plant using deep reinforcement learning. *Water Science and Technology*, 81(8), 1578–1587. https://doi.org/10.2166/wst.2020.053

Nam, K. J., Heo, S. K., Kim, S. Y., & Yoo, C. K. (2023). A multi-agent AI reinforcement-based digital multi-solution for optimal operation of a full-scale wastewater treatment plant under various influent conditions. *Journal of Water Process Engineering*, 52, 103533. https://doi.org/10.1016/j.jwpe.2023.103533

Qiao, J., Yang, R., & Wang, D. (2023). Offline data-driven adaptive critic design with variational inference for wastewater treatment process control. *IEEE Transactions on Automation Science and Engineering*. https://doi.org/10.1109/TASE.2023.3305615

Raes, L., & McAleer, S.R. (2025). Introduction: Defining local digital twins, in: Raes, L., Ruston McAleer, S., Croket, I., Kogut, P., Brynskov, M., Lefever, S. (Eds.), *Decide Better: Open and Interoperable Local Digital Twins*. Springer Nature Switzerland, Cham, pp. 1–5. https://doi.org/10.1007/978-3-031-81451-8_1

Rehman, U. (2016). *Next Generation Bioreactor Models for Wastewater Treatment Systems by Means of Detailed Combined Modelling of mixing and Biokinetics*. PhD. Thesis, Ghent Universi-ty, Belgium.

Sparks, J. (2024). *The Intersection of Industrial Control, Data-Driven Modelling, and Digital Twins at Water Resource Recovery Facilities: Achieving Next-Gen Biological Nutrient Removal with Balanced Complexity*. PhD. Thesis, Université Laval, Québec, QC, Canada.

Sparks, J., Bott, C. B., & Vanrolleghem, P. A. (2025) Design considerations for a Digital Twin built to improve nitrification performance at a water resource recovery facility. *Water Science and Technology*, 92, 471–491.

Stentoft, P. A., Guericke, D., Munk-Nielsen, T., Mikkelsen, P. S., Madsen, H., Vezzaro, L., & Møller, J. K. (2019). Model predictive control of stochastic wastewater treatment process for smart power, cost-effective aeration. *IFAC-PapersOnLine*, 52(1), 622–627, https://doi.org/10.1016/j.ifacol.2019.06.132.

Stentoft, P. A., Munk-Nielsen, T., Møller, J. K., Madsen, H., Valverde-Pérez, B., Mikkelsen, P. S., & Vezzaro L. (2021). Prioritize effluent quality, operational costs or global warming? – Using predictive control of wastewater aeration for flexible management of objectives in WRRFs. *Water Research*, 196, 116960. https://doi.org/10.1016/j.watres.2021.116960

Sutton, R. S., & Barto, A. G. (2018). *Reinforcement Learning: An Introduction* (2nd ed.). MIT Press, Cambridge, MA, USA.

Torfs, E., Nicolaï, N., Daneshgar, S., Copp, J. B., Haimi, H., Ikumi, D., Johnson, B., Plosz, B. B., Snowling, S., Townley, L. R., Valverde-Pérez, B., Vanrolleghem, P. A., Vezzaro, L., & Nopens, I. (2022). The transition of WRRF models to digital twin applications. *Water Science and Technology*, 85(10), 2840–2853. https://doi.org/10.2166/wst.2022.107

Wang, A. J., Li, H., He, Z., Tao, Y., Wang, H., Yang, M., Savic, D., Daigger, G. T., & Ren, N. (2024). Digital twins for wastewater treatment: A technical review. *Engineering*, 36, 21–35. https://doi.org/10.1016/j.eng.2024.04.012

Wang, D., Li, X., Xin, P., Liu, A., & Qiao, J. (2024a). Supplementary heuristic dynamic programming for wastewater treatment process control. *Expert Systems with Applications*, 247, 123280. https://doi.org/10.1016/j.eswa.2024.123280

Wang, D., Ma, H., Ren, J., Gao, N., & Qiao, J. (2024b). Adaptive critic design with weight allocation for intelligent learning control of wastewater treatment plants. *Engineering Applications of Artificial Intelligence*, 133, 108284. https://doi.org/10.1016/j.engappai.2024.108284

Ward, B. J., Andriessen, N., Tembo, J. M., Kabika, J., Grau, M., Scheidegger, A., Morgenroth, E., & Strande, L. (2021). Predictive models using “cheap and easy” field measurements: Can they fill a gap in planning, monitoring, and implementing fecal sludge management solutions? *Water Research*, 196, 116997. https://doi.org/10.1016/j.watres.2021.116997

Xu, J., Wang, H., Rao, J., Deng, C., Huang, F., Shen, Q., & Zhang, L. (2021). Zone scheduling optimization of pumps in water distribution networks with deep reinforcement learning and knowledge-assisted learning. *Soft Computing*, 25, 14757–14767. https://doi.org/10.1007/s00500-021-06177-3

Yang, C., Johnson, B., Registe, J., Johnson, T., Rahman, A., & Kenyon, J. (2023). Soft sensing influent concentrations with airflow rates by digital twins: A real case study from Oldham WwTW. *Water Environment Federation’s Technical Exhibition and Conference (WEFTEC2023)*. Water Environment Federation. https://doi.org/10.2175/193864718825159227

Zhuang, Z., Sun, Z., Cheng, Y., Yao, R., & Zhang, W. (2018). Modeling and Optimization of Paper-making Wastewater Treatment Based on Reinforcement Learning. *2018 37th Chinese Control Conference (CCC)*, Wuhan, China, July 25–27.

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Digital water and innovation in potable reuse

Authors: *Germano Salazar-Benites, Shalongo Angula, and Brian Pecson on the behalf of the Water Reuse Specialist Group*

Introduction

There's been a surge of momentum around water reuse initiatives globally in recent years. But at the heart of the conversation remains a key question: Is water reuse the right thing to do – or is it the smart thing to do? At first glance, these two questions might seem interchangeable; however, they reflect fundamentally different perspectives. Doing what's right talks about the principles of ethics, environmental responsibility, and long-term sustainability. Doing what's smart speaks to innovation, practicality, and the strategic advantages that water reuse brings to communities, industries, and ecosystems alike.

In places like California, this debate has largely been settled – not by choice, but by necessity. Recurring droughts, population growth, and intensifying climate pressures have made water reuse an indispensable component of the state's long-term water strategy. This shift has prompted the development of more sophisticated and proactive regulatory frameworks, designed not just to protect public health but to maximise the value of every drop of water available.

Potable reuse regulations rely on a multiple-barrier approach to protect public health. In indirect potable reuse (IPR), this approach typically involves the simultaneous use of multiple barriers: robust *treatment, monitoring* of process performance and water quality, *source control* programmes, and the *environmental buffer* (e.g. the groundwater aquifer or surface water reservoir). The distinguishing feature of direct potable reuse (DPR), however, is the absence of the environmental buffer, meaning that DPR removes one of the key public health barriers for IPR. DPR regulations typically compensate for this lost benefit by increasing the stringency of the remaining barriers. California's DPR regulation, for example, requires additional pathogen treatment – beyond the minimum needed to protect public health – to provide a buffer against short-term failures. But what if something still goes wrong? In IPR, water is retained in the environment for extend periods (often months or years) before it is distributed to consumers. This retention of water in the environment provides an extended period of time for IPR systems to identify and address any events (e.g. excursions, failures) that may compromise water quality before the water is sent to consumers. In DPR, however, the water may be integrated into the supply within hours, requiring systems to respond to failures on time scales that are orders of magnitude shorter than IPR.

These evolving regulations have catalysed a wave of innovation across the water sector. Engineers are breaking new ground in advanced water treatment technologies to meet increasingly stringent water quality standards. Meanwhile, analytical chemists are pushing the limits of quantification, creating testing methods that can identify contaminants at previously undetectable levels. This has created a powerful feedback loop: as scientific tools improve, so do regulatory expectations. Public trust and scientific progress drive regulators to raise the bar, pushing the industry to not only comply but to innovate proactively. The result is a dynamic ecosystem of continuous improvement, where water reuse systems are becoming more reliable, more efficient, and more adaptable for a wide range of applications.

Amid this rapidly evolving landscape, the original question comes into sharper focus: Water reuse isn't just the right thing to do or the smart thing to do. It's both and it's here where the true potential of digital water and innovation becomes clear. Digital solutions, such as smart sensors, real-time data analytics, artificial intelligence, and automation, are transforming how water reuse systems are managed and optimised.

Key insights

Digital solutions are becoming essential for process optimisation in response to evolving industry challenges:

1. **Rising regulatory concerns**
   Stricter environmental regulations and lower quantification limits for specific contaminants are pushing utilities to find more efficient and compliant ways to operate.
2. **Energy efficiency as a strategic priority**
   Reducing energy use is no longer just a cost-saving measure, it's central to sustainable operations and long-term resilience.
3. **Accelerated shift toward water reuse**
   With more utilities pursuing water reuse initiatives, optimising treatment processes is critical to meet strict water quality standards and to ensure reliability.
4. **Smarter operations are now a necessity**
   To remain compliant, cost-effective, and future-ready, utilities must adopt intelligent, data-driven approaches to treatment plant management.

Case studies

The following case studies illustrate how cutting-edge digital innovations and operational strategies are rising to meet different challenges, enhancing treatment plant performance, safeguarding public health, and advancing water reuse in the face of evolving regulatory and operational demands.

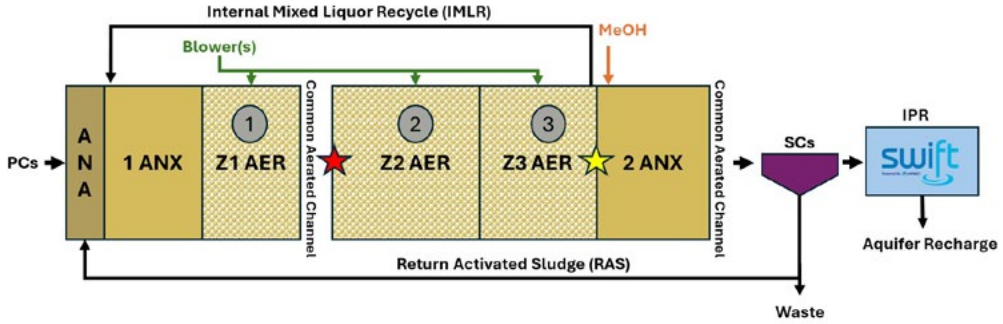
Case study 1: Digital twin deployment for enhanced nitrification performance at HRSD Nansemond Treatment Plant (NTP)

The Hampton Roads Sanitation District (HRSD) Nansemond Treatment Plant (NTP), located in Eastern Virginia, USA, deployed a digital twin (DT) purpose-built for optimising its nitrification process. The NTP operates a five-stage Bardenpho process with a design flow of approximately 114,000 m^3/day (30 MGD).

By 2029, the NTP intends to redirect all dry weather flow for groundwater aquifer recharge and IPR, which requires the instantaneous total inorganic nitrogen (TIN) concentration in the secondary effluent to be no greater than 5 mg/L.

The specific operational objectives included:

1. Minimising energy consumption while achieving secondary effluent nitrogen targets.
2. Reducing chemical consumption (sodium hypochlorite) by maintaining positive ammonia (NHx) entering chlorine disinfection to promote cost-saving chloramine formation.
3. Improving ammonia-based aeration control (ABAC) and providing valuable data for future facility expansions.



Key	
★	NHx_0 OR $Z2_{inf}$ NHx – Location of NHx measurement for *feedforwarded* ABAC in Z2 AER (1 total)
★	$Z3_{ef}$ NHx – Location of NHx measurement for feedback ABAC in Z2 & Z3 AER (1 per train, 4 total)
1	Rule-based DO controller deployed here that assigns either a min or max DO_{SP} based on time-of-day (DO_{SP} →ACV_{pos}).
2	Hybrid model-based feedforward-feedback ABAC controller deployed here (NHx_{SP}→DO_{SP}→$Q_{AIR\text{-}SP}$→ACV_{pos})
3	Strict feedback PI ABAC controller deployed here (NHx_{SP}→DO_{SP}→$Q_{AIR\text{-}SP}$→ACV_{pos}).

Abbreviations	
PCs	Primary Clarifiers
SCs	Secondary Clarifiers
MeOH	Methanol
ABAC	Ammonia-Based Aeration Control
DO_{SP}	Dissolved Oxygen Setpoint
ACV_{pos}	Aeration Control Valve Position Setpoint
NHx_{SP}	Ammonia Setpoint (for ABAC)
$Q_{AIR\text{-}SP}$	Air Flow Setpoint

Figure 2.7: Five-stage Bardenpho at the HRSD NTP with (cascade) controller information included. (Figure adapted from Sparks, Bott, & Vanrolleghem (2025).

CHALLENGES

Prior to the DT, NTP used a feedback proportional integral (PI) ABAC controller and experienced frequent loss of control authority—defined as the system's ability to respond to disturbances using inputs like dissolved oxygen (DO).

Modeling and analysis revealed four key barriers:

- Suboptimal tuning: Despite years of tuning, performance gains were limited.
- Variable process conditions: Nitrogen loads vary up to 400% daily due to diurnal flow and rising total Kjeldahl nitrogen, TKN. With no flow equalisation and a plug flow-like system (*11 continuous stirred-tank reactors, CSTRs,* in series), sensor lag (5+ hours) hindered real-time response.
- Restricted DO setpoints: The NHx controller's minimum DO setpoint is 0.3 mg/L-O_2, likely too high given nitrifier needs (~0.1 mg/L-O_2), limiting low-end control authority. The upper limit of 2 mg/L-O_2 is appropriate.
- Ineffective solids retention time (SRT) and waste rate control: manual, experience-based waste adjustments led to inconsistent SRT and nitrifier levels, reducing controller stability.

SOLUTION: DIGITAL TWIN ARCHITECTURE AND FUNCTIONS

The DT deployed at HRSD's Nansemond Treatment Plant is designed specifically to optimise nitrification. Built on the Activated Sludge Model No. 1 (ASM1) using Sumo© software, the model replicates the plant's liquid treatment train – including primary clarifiers, biological reactors, and secondary clarifiers. The DT operates on a dedicated server and receives real-time data from the plant's distributed control system every minute via open platform communications, enabling timely and data-driven decision-making.

The DT has two primary functions. First, it serves as a soft sensor, continuously estimating the maximum specific growth rate of nitrifiers (µmax-NITO). This dynamic insight into biological kinetics allows for more targeted and responsive feedforward ABAC. Second, the DT includes a waste rate recommender system, which analyses operating conditions and suggests optimal sludge wasting rates to maintain sufficient nitrifier biomass. These recommendations help preserve and enhance NHx control authority across a wide range of process scenarios.

Using high-performance computing, the DT runs 1,000 dynamic simulations in less than 24 hours, testing different waste rates, DO levels, and influent nitrogen loads. Its goal is to ensure 100% daily ABAC control authority, balancing ammonia reduction under high load with flexibility under low load to prevent over-nitrification.

To further support proactive decision-making, the DT integrates temperature forecasting over a three-SRT horizon. Since a full microbial turnover takes approximately three SRTs, this forecasting capability enables the plant to anticipate and adapt to seasonal temperature variations that impact maximum nitrifier growth rate. By planning ahead, operators can adjust waste rates before conditions change, preserving control authority and maintaining process stability throughout the year.

Case study 2: Strategic positioning of AMOZONE process model for optimising ozonation micropollutant removal and bromate formation

Process modelling underpins the scientific and engineering foundations of water and wastewater treatment processes. Through process modelling, utilities and engineers can evaluate various design and operational scenarios prior to implementation, assess the trade-offs between energy use, costs, and water quality, and ensure compliance with stringent regulatory standards. In reuse systems – where advanced treatment processes such as ozonation, activated carbon adsorption, and membrane filtration are employed – advanced modelling and DTs are becoming valuable decision support tools for design, optimisation, operational control, and regulatory compliance.

The Hapert Wastewater Treatment Plant (WWTP) in the Netherlands (operated by the De Dommel Water Authority (WSDD)) and HRSD's Nansemond SWIFT facility in the USA serve as excellent examples of how advanced process modelling can support water reuse projects throughout their entire lifecycle – from feasibility assessment and design to real-time operation – ultimately enhancing both efficiency and reliability.

HAPERT WWTP

At Hapert WWTP, the primary objective was to minimise the discharge of micropollutants into the receiving water body while simultaneously preventing excess bromate formation during the ozonation process. To achieve this, the utility utilised the computational fluid dynamics (CFD) based ozonation process model (AMOZONE-CFD) to design and optimise a full-scale ozonation reactor. The project included detailed simulations that informed the design of a co-current ozone injection system, which aimed to enhance micropollutant removal while reducing both bromate formation and ozone consumption.

Following this, a DT was developed that integrates real-time operational data with the calibrated model. This DT is now employed for operator training and preparatory purposes. Additionally, various scenario analyses for the Hapert ozonation reactor are being conducted using the dynamic model of the DT to optimise micropollutant removal and minimise bromate formation. The DT has also facilitated the testing of different ozone dosages through long-term dynamic simulations, enabling the determination of the minimum required dose to maintain bromate formation below 1µg/l while ensuring that micropollutant removal remains above the utility's target.

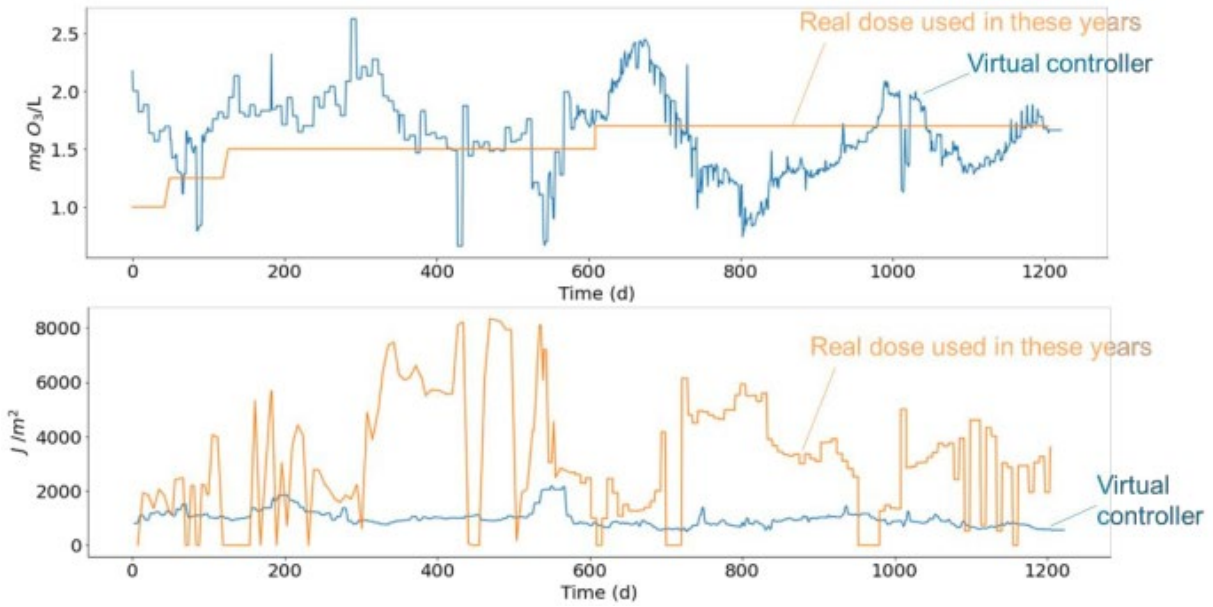


Figure 2.8:. Long-term simulations using AMAZONE for operational optimisation demonstrate potential savings in ozone (top) and UV (bottom) dosing in the peroxone-UV/H_2O_2 reactor. These simulations feature a virtual controller designed to maintain target effluent quality while minimizing operational expenses (OpEx) in the peroxone reactor. (Figure adapted from Muoio et al., 2025a)

HRSD NANSEMOND SWIFT

The HRSD Nansemond SWIFT project is applying the AMOZONE-CFD modelling tool to support IPR. This facility processes secondary effluent to meet drinking-water standards for managed aquifer recharge. To ensure efficient removal of trace organic contaminants while adhering to stringent bromate limits, the ozonation model was thoroughly calibrated and validated using data from pilot-scale studies (Figure 2.9). This calibrated model then informed the design of the full-scale reactor, optimising aspects such as diffuser placement, baffle configuration, and flow regimes. By performing a wide range of virtual scenarios, the project team could explore numerous design and operational modifications (e.g. co-current vs counter-current injection, optimal H_2O_2/O_3 and O_3/DOC ratios) without costly physical experimentation. This de-risks the design process and ensures the final facility is robust and optimised from the start.

Case study 3: event detection systems for DPR

One of the key technical challenges for DPR is developing new monitoring and control systems that can detect and respond to failures under very short time-scales.

CHALLENGE

While current monitoring can continuously track unit process performance, the integration of this information across the entire treatment train is not typically conducted in real-time. Consequently, potable reuse systems are not receiving advanced warning of failures. Furthermore, current monitoring and control systems often do not identify the cause of the failure, which can range from treatment failures to monitoring issues to water quality variations.

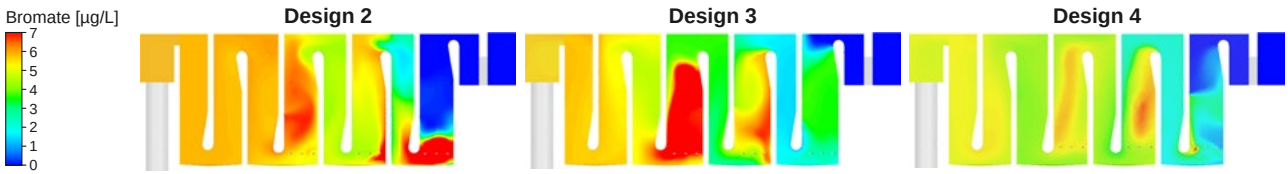


Figure 2.9: AMOZONE-CFD simulations showing bromate formation across multiple design scenarios. (Figure adapted from Muoio et al., 2025b)

SOLUTION: EVENT DETECTION SYSTEMS FOR DPR

As a general rule, the time that it takes to respond to a failure must be shorter than the time it takes the water to go to distribution. For example, if water spends an hour in a treatment facility before going to distribution, then we need to be able to detect and respond to any failures within an hour. The time to respond to an event is comprised of two consecutive steps: the *detection* and the *resolution* of the event. In IPR systems, the response time has to be shorter than the retention time in the environment, meaning that facilities often have multiple months to respond while the water travels through the aquifer. The issue with applying IPR response frameworks to DPR is that they may not be fast enough for the short timescales available. Two approaches that can be used in DPR to shorten response times are to (1) detect events earlier and (2) resolve events faster (Figure 2.10). A recent research study explored the development of an **event detection system** for DPR that addresses short retention times by providing advanced warning of potential issues and reducing the time needed to resolve them (Pecson, Pisarenko et al. 2024).

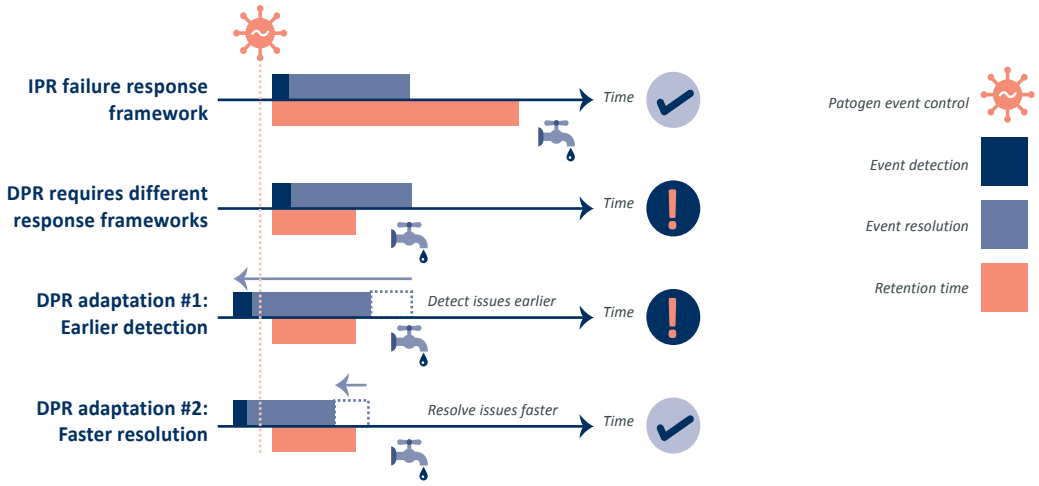


Figure 2.10. Response time frameworks need to be adapted to address short retention times in DPR.

The study categorised events (e.g. failures) into three main groups: (1) treatment failures, (2) monitoring failures, and (3) water quality issues, all of which may occur at a given unit process. For example, an ozone system could have a failure of the ozone generator that drops the ozone dose below what is needed for disinfection (treatment failure); it could have an ozone meter that is inadvertently put on hold and not reading the actual conditions (monitoring failure); or it could be subjected to an unanticipated peak of chemicals that it is not designed to address (water quality issue). The study used performance data from the City of San Diego's 3,800 m^3/day (1 million gallon per day) DPR demonstration facility, which consists of ozone, biological activated carbon, membrane filtration, reverse osmosis, and a UV-based advanced oxidation process. The project developed an automated, digital system for differentiating these three types of events. Data management software was installed on a computer that was connected to the unit process programmable logic controller (PLC) and used to log data every minute. Algorithms were developed in Python to detect the different types of events using the plant's performance data.

A matrix of pathogen failures was developed to guide the development of algorithms to detect each of the three types of failures for ozone, microfiltration (MF), reverse osmosis (RO), and ultraviolet / advanced oxidation process (UV/AOP). The testing included the use of actual process excursions and challenge tests to validate the event detection system. Traditional monitoring systems rely on operations staff reacting to alarms and subsequently troubleshooting to recognise the source of failure. A review of historical operating data identified five distinct patterns of anomalous behavior that typically signalled a potential event:

- **Data stagnation:** data signal lacks variability over a given time period
- **Rapid data changes:** rate of change over short time period exceeds typical value
- **Exceedance of thresholds:** data fall above or below statistical norms for process
- **Data drifts:** slow, persistent change in data over extended period
- **Unusually volatile data:** data is unusually noisy over extended period of time.

To automate the process, algorithms were developed to identify each of these data trends for event detection. The event detection system successfully identified all 11 types of failure and provided information on the type and time of the event as well as additional information to diagnose and resolve the issue. For example, the use of statistical process control allowed the system to detect an ozone metering issue nearly an hour before it exceeded a regulatory threshold and immediately informed the operators that meter drift at a specific meter was the cause of the issue. By providing both **early detection** and **automated identification** of the issue, the system met the key criteria needed to adapt DPR frameworks to the short times available for failure response.

Conclusions

Digital solutions and modelling are transforming the water sector including the emerging field of potable water reuse. Given the higher level of treatment needed compared to conventional drinking water supplies, potable reuse systems are often more costly and complex. Digital solutions are helping to making them safer, more efficient, and adaptable amid evolving regulations and environmental challenges. These case studies collectively demonstrate the transformative impact of digital innovation and advanced modeling in water reuse management. The DT at HRSD's Nansemond Treatment Plant and the use of CFD to design a full-scale ozonation reactor exemplify how targeted, model-driven solutions can optimise complex biological processes, enhance operational stability, and meet increasingly stringent regulatory demands through proactive, data-informed decision-making.

At the same time, the emerging implementation of DPR systems across the globe have highlighted the urgent need for new functionality in monitoring and control. Due to the absence of the environmental buffer in DPR settings, rapid, automated event detection systems are needed that can respond to treatment failures within significantly shorter timeframes. These novel challenges underscore the growing role of digital tools in protecting public health where traditional environmental buffers are absent.

Together, these examples illustrate a broader shift from empirical, reactive operations to predictive, model-based water management that integrates scientific principles, real-time data, and digital technologies. These tools enable continuous monitoring, early anomaly detection, predictive maintenance, and more efficient use of energy and chemicals. Digital solutions provide the intelligence and responsiveness needed to operate advanced water systems safely, sustainably, and efficiently at scale. By embracing digital water and innovation, we're not just doing the right thing – or the smart thing – we're building the future of water.

References

Pecson, B., et al. (2024). Integration of high-frequency performance data for microbial and chemical compound control in potable reuse treatment systems. The Water Research Foundation. Alexandria, VA, The Water Research Foundation.

National Research Council. (2012). Water reuse: Potential for expanding the nation's water supply through reuse of municipal wastewater. The National Academies Press. https://doi.org/10.17226/13303

Angelakis A.N., Asano T., Bahri A., Jimenez B.E. and Tchobanoglous, G. (2018) Water reuse: from ancient to modern times and the future. *Frontiers in Environmental Science*, 6:26. https://doi.org/10.3389/fenvs.2018.00026

Trussell, R. S., Salveson, A., & Trussell, R. R. (2020). *Potable reuse: A new paradigm for a water-scarce world*. AWWA Press.

California State Water Resources Control Board. (2023). Water reuse in California: Status, challenges, and opportunities. https://www.waterboards.ca.gov/

Sparks, J., Bott, C.B., and Vanrolleghem, P.A., (2025). Design considerations for a digital twin built to improve nitrification performance at a water resource recovery facility, *Water Science and Technology* 92, 471–491, https://doi.org/10.2166/wst.2025.106

Muoio, R., Bellandi, G., Pearce, R., Murphy, D., Vlasschaert, P., Bott, P., Lewis, T. & Audenaert, W. (2025). Full-scale of ozonation reactor design with CFD-AMOZONE for the HRSD Nansemond SWIFT indirect potable reuse facility. In *Proceedings of the Water Environment Federation's Annual Technical Exhibition and Conference (WEFTEC) 2025*.

Muoio, R., Bellandi, G., Pearce, R., Schemen, R., van Horne, P., Vlasschaert, P., & Audenaert, W. (2025). From feasibility study to full-scale ozonation plant design, and digital twin for maximum micropollutant removal and minimal bromate formation. In *Proceedings of the 7th International Advanced Oxidation Processes* (AOP7)

| 2.3 |

Emerging trends in water treatment modelling: novel models, architectures and applications

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Introduction

The global water sector is undergoing structural and functional changes to transition to an integrated approach to water management that recognises the connections between all facets, considering the system as interconnected whole. Modelling is central to this transformation, with applications expanding far beyond traditional process design and optimisation. Emerging approaches now support public health through wastewater-based epidemiology, enhance drinking water safety via flow sheet modelling, enable circular economy strategies through resource recovery modelling, strengthen sustainability by integrating nature-based solutions, and aid water quality data collection, monitoring and control with soft-sensor development. At the same time, the modelling community needs and is therefore advancing good practices and exploring new paradigms, including the rise of data-driven and hybrid models that combine mechanistic understanding with machine learning. These developments present both opportunities and challenges, requiring careful attention to transparency, calibration, validation, and integration into decision-making frameworks.

Modelling in the water sectors needs to keep up with current globally disrupting trends of generative AI while ensuring full safety. This contribution, developed by the IWA Specialist Group on Modelling and Integrated Assessment (MIA), reflects a shared commitment to advancing modelling as a trusted, innovative, and impactful tool for the water sector. By highlighting emerging applications, promoting good modelling practices, and critically examining new paradigms, it aims to ensure that models remain robust, transparent, and fit-for-purpose while supporting sustainable, resilient, and informed water management worldwide.

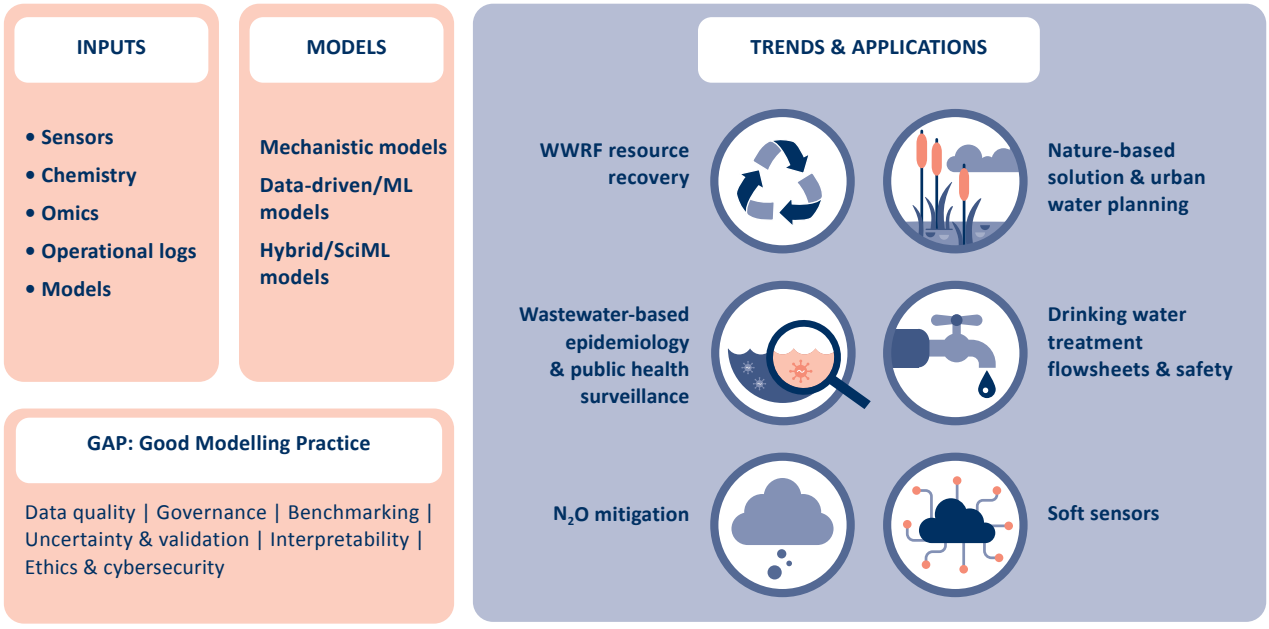


Figure 2.11: Graphical abstract: emerging trends in water treatment modelling

Emerging model applications

Wastewater-based epidemiology modelling

How people see wastewater throughout history depends strongly on the epoch and spans from waste to be disposed of, over a source of valuable materials and energy, to more recently a valuable (and relatively anonymous) source of information about public health. Wastewater-based epidemiology (WBE) consists of estimating a population's exposure to a disease or substance by measuring the presence of an indicator substance in wastewater. WBE has seen three main usages in recent years: communicable disease monitoring, chemical exposure monitoring, and metagenomics. Among these three, the most visible has recently been the monitoring of communicable diseases, most notably of COVID-19. Beyond the mere conversion of raw wastewater signals to prevalence estimates (Ahmed et al., 2020b; Morvan et al., 2022), mathematical models enable several uses of WBE to support public health, including directly estimating the reproductive number with time series modelling (Huisman et al., 2022), predicting single outbreaks through short-term forecasting using linear and wave models (Joseph-Duran et al., 2022) and generating early warnings in case of outbreaks using, for instance, principal components analysis (Bosch et al., 2024). The complex non-linear dynamics, e.g. from population movements, in-sewer processes and measurement noise can be handled using auto-regressive smoothing (Cluzel et al., 2022; Courbariaux et al., 2022), by normalising the signal with respect to population or fecal load (Maere et al., 2022), or by combinations thereof (Rauch et al., 2022). Decoding the impact the sewer environment has on the fate of WBE markers is also critical to map WBE signals to on-the-ground situations upstream (Tik et al., 2024).

Besides disease monitoring, WBE can help assess how chemical substances that impact human and environmental health such as illicit drugs (McCall et al., 2016; Zarei et al., 2020), contaminants of emerging concern (Senta et al., 2020), and pharmaceutical compounds (Ahmed et al., 2020a) circulate in sewersheds, providing a lens on the real-life impacts of environmental legislation, law enforcement actions, and public health policies. However, in analytical chemistry, non-target and suspect screening approaches introduce major mathematical and computational challenges, especially in wastewater surveillance, where chemical complexity and matrix effects are extreme. Wastewater magnifies this complexity, with diverse chemical backgrounds. The result is a genuinely data-intensive analytical environment in which machine-learning tools, spectral-networking workflows, and high-performance computing become essential to extract meaningful signals while dynamic environmental matrices and variable loads push statistical models to their limits, demanding tight integration of chemistry, informatics, and modelling.

A third application based on metagenomic sequencing techniques allows researchers to directly monitor changes in the prevalence of certain genes in wastewater (Riquelme et al., 2022), fundamentally altering the fight against antimicrobial resistance from a reactive mode based on clinical reporting to a more proactive approach following the emergence of resistance genes in real time within sewersheds (Gholipour et al., 2024). However, microbiome and resistome analysis in wastewater presents several fundamental mathematical and statistical challenges that go beyond those typically encountered in classical environmental monitoring. Sequencing datasets are compositional, constrained by sequencing depth, and only relative abundances are observed – requiring specialised methods to avoid spurious correlations (Munk et al., 2025).

With so many avenues for development, WBE is set to become a fundamental component of the public health monitoring toolkit. However, as the precision and analytical power of WBE grow, so does the potential to harm vulnerable populations. Ethical frameworks and standards of practice must be developed around WBE to protect people's right to privacy and Indigenous peoples' sovereignty over their own data and health (Centre TFNIG, 2019; D'Aoust, 2025).

Foundational process models for water resource recovery facilities

The transition from wastewater treatment plants (WWTPs) to water resource recovery facilities (WRRFs) must provide long-term ecosystem protection and deliver context-specific and viable technologies within a circular economy. Adoption is slowed by biochemical complexity, scale-up issues, and changing market conditions and regulations, especially for high-value products. Mathematical modelling can reduce these uncertainties and complement experiments by organising knowledge to improve understanding, design, prediction and optimisation. Below, we outline three modelling frameworks for emerging biological and physicochemical processes that support this transition.

1. Traditional models focus on simplified biology and include only minimal physicochemical reactions (e.g. Henze et al., 2000). For certain resource recovery processes this does not suffice: e.g. capturing mineral precipitation in WRRF digesters on a thermodynamic basis (Flores-Alsina et al., 2016); optimising P recovery strategies through plant-wide phosphorus interaction representation (Lizarralde et al., 2019; Solon et al., 2017); acid recovery; or CO_2 capture through modelling of electrochemical processes (Brewster et al., 2016). To unify these efforts, the IWA task group on physical chemical modelling developed the generalised physicochemical modelling framework for WRRF applications (Batstone and Flores-Alsina, 2022).

2. Beyond converting sludge to biogas and biosolids, WRRFs can produce biopolymers that substitute non-renewable plastic sources. Using mixed microbial cultures, operators can now apply strategies to enrich communities to maximise biopolymer accumulation. For this optimisation task, two processes are specifically relevant: (1) intracellular storage of polymers such as polyhydroxyalkanoates (PHA), and (2) secretion of extracellular polymeric substances (EPS). Reliable prediction of PHA production depends on well-characterised substrates (Jiang et al., 2011; Wang et al., 2018). EPS modelling is challenging due to its structural complexity and the absence of a clear way to include the process in current dynamic frameworks. Improved EPS characterisation is needed (Zahra et al., 2024) to develop more accurate models for EPS formation, degradation, and hydrolysis (Mannina et al., 2023).

3. Phototrophic systems are emerging technologies that use light to recover resources and upcycle them into high-value products such as biofuels, fertilisers, or microbial feeds. Their microbial and metabolic diversity, reflected in different microbial clades (e.g. microalgae, purple bacteria, or cyanobacteria) and growth strategies (e.g. photoautotrophy, or photoheterotrophy), improves their resilience and broadens their applicability, but also makes them challenging to study due to the partial observability. Additionally, abiotic factors such as sunlight and temperature affect multiple biological processes simultaneously making control and optimisation challenging (Shoener et al., 2019). Some first mechanistic modelling efforts following activated sludge model (ASM)-style frameworks have been undertaken (e.g. Wágner et al., 2016). Recently, efforts were made to combine an integrated model of anaerobic digestion and microalgae cultivation to optimise microalgal biorefineries (Carecci et al., 2024). Another trend uses data-driven and hybrid modelling approaches to describe the complex interplay between abiotic and biological factors. Yet, data availability is still a major challenge to track crucial factors such as microbial diversity or biomass quality (Casagli et al., 2025).

While modelling frameworks are well established for WWTPs, the transition to WRRF requires tools tailored to new goals and operating needs. A major challenge is the limited availability of high-quality and reconciled FAIR datasets across multiple targets.

Modelling for nature-based solutions' planning and design

Nature-based solutions (NBS) play a key role in closing water cycles, providing ecosystem services, and helping to shape a sustainable and resilient approach to water management (Lippera et al., 2025; Panduro and Veie, 2013). NBS encompass actions and nature-inspired technologies to protect, manage, and restore ecosystems while addressing societal challenges and providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). Decision- and planning-support systems are being developed to facilitate NBS integration into urban infrastructure planning (e.g. Mannina et al., 2019; Rosse et al., 2023).

The modelling landscape is moving towards integrated assessment showcasing multi-functionality. Emerging tools include Nat4Wat (Pueyo-Ros et al., 2026); UrbanINVEST (Tallis et al., 2011); BGIS (Alves et al., 2024); and UrbanBEATS (Bach et al., 2020). Major projects like EU RECONNECT, the Natural Capital Project, and MultiGreen are underpinning these efforts. However, challenges persist regarding implementation guidance (Istenič et al., 2023), limited data and knowledge, and comprehensive evaluation of life-cycle costs, benefits, and ecosystem services. Consequently, NBS design remains conservative, based on simple rules.

EPA SWMM remains the dominant stormwater tool for NBS incorporation, with various enhancements developed (e.g. SWMM-UrbanEVA; Hörnschemeyer et al., 2021). Process-based biokinetic models exist for specific systems like treatment wetlands (Langergraber et al., 2009) but require significant computational time. For model-based design objectives with a long-term perspective, the inclusion of clogging mechanisms is under consideration (Samsó et al., 2016). Simpler empirical models like first-order exponential decay (Kadlec and Wallace, 2009) are more widely used despite being less mechanistic. Tafti et al. (2024) give an overview.

Machine learning models offer another option for process-based approaches, with tree-based models showing strong performance for treatment wetlands (Nguyen et al., 2022). However, data quality and quantity remain limiting factors (Bahramian et al., 2023). Hybrid models (Guillaume-Ruty, 2025) and Generative AI (Prodanovic et al., 2024) represent emerging approaches to improve reliability and bridge domain knowledge for quantifying multi-functional potential.

Flow sheet modelling of drinking water treatment plants

For decades, drinking water treatment plants (DWTPs) have guaranteed access to sufficient and safe drinking water. However, today, water utilities face growing challenges. Climate change and its associated extreme weather events, combined with projected population growth, are placing increasing pressure on raw water sources (Makarigakis and Jimenez-Cisneros, 2019). Meanwhile, regulations are becoming stricter: worldwide, the number of monitored parameters continues to rise, while permissible limits steadily decrease (US Environmental Protection Agency, 2009; Qu et al., 2012; European Parliament and Council, 2020). Reaching these limits, especially for disinfection by-products, requires optimising treatment plant operations, yet full-scale experimentation is highly limited due to health and safety concerns.

In this context, mathematical modelling and integrated process and system simulation emerge as relevant tools for enhanced decision-making in DWTPs. Surprisingly, the adoption of such tools is significantly less widespread than in the wastewater treatment sector. Common reasons include the limited number of interconnected models, excessive reliance on empirical approaches, and difficulties in usability or extending them with new technologies (Dudley et al. 2008). The DriWM® (Elduayen-Echave and Ayesa, 2025) framework overcomes these main challenges. The framework is dynamic, which facilitates the systematic interconnection of the different unit process models; it relies on the mechanistic description of the main unit processes, rather than regressions or user-defined yields; and it is flexible and expandable, which should facilitate future developments and implementations.

The key aspect of the DriWM® framework is the novel fractionation of natural organic matter (NOM). A fractionation of NOM is necessary to construct a common component vector that is compatible with the entire treatment train. The framework is currently composed of 50 components and a list of chemical transformations describing oxidation (with three different oxidants), disinfection by-product formation, coagulation, flocculation, clarification, and adsorption processes. The model is defined using a Gujer matrix, composed of a stoichiometry matrix and a vector of kinetics. This enables rigorous and systematic assembly of virtual DWTPs from compatible unit process models.

Changing modelling paradigms

The previous sections demonstrated that new model applications, such as WBE and circular water and resource management, are driving the need to extend existing models and incorporate fresh process insights. Simultaneously, the very frameworks of modelling are evolving. Traditional first-principle approaches are increasingly being replaced, augmented, or complemented by data-driven and hybrid architectures. This convergence of mechanistic understanding with machine learning and statistical inference marks a shift toward flexible, adaptive, and predictive modelling paradigms which in turn creates new opportunities for model application.

Data-driven and hybrid model approaches for the water sector

Over the past decade, modelling with data-driven components has become increasingly integrated into the water sector, supporting a wide range of applications such as digital process monitoring (e.g. soft sensors), process optimisation and control, predictive maintenance of assets, forecasting of influent characteristics and operational disturbances, and decision support.

Supervised machine learning (ML), where the model is derived only from the data it is trained on, offers an alternative for predictive modelling based on first principles. Corominas et al. (2018), Alvi et al., (2023), and Venrolleghem et al., (2025) critically review machine learning techniques and applications for water treatment. Reinforcement learning has recently started to be adopted in the water sector as a promising approach for dynamic process optimisation and control (Hernández-del-Olmo et al., 2012; Chen et al., 2021; Croll et al., 2024). The availability of data types other than conventional tabular data – such as images, sequencing data, or operator logs has inspired water practitioners to start adopting approaches such as computer vision (e.g. convolutional neural networks, CNNs), or generative models (e.g. transformers and large language models, LLMs) supporting planning, reporting and decision making (Borzooei et al., 2024; Zhu et al., 2024).

Therefore, the development of composite models that are currently called hybrid models has gained momentum in recent years (Schneider et al., 2022). At the root, these models rely on domain knowledge, by which we mean the inclusion of, among others, physical principles, symmetries (e.g. mass balances), constraints, uncertainties, or expert training. Acquiring this domain knowledge is often time-consuming, and the resulting models may suffer from complexity, brittleness, and impractical calibration. Data-driven models can potentially be implemented rapidly but depend heavily on large datasets, are characterised by lower interpretability, and perform reliably only within the range of the training data. Hybrid modelling offers a way to balance these contrasting strengths and limitations, potentially improving model prediction accuracy, calibration efficiency, extrapolation capability, and interpretability (Von Stosch et al., 2014), but require the understanding of two paradigms.

Among hybrid model architectures, in parallel or delta models mechanistic and data-driven components are trained independently (e.g. Serrao et al., 2024). While effective for predictive accuracy, they offer limited insight into underlying processes and properties, such as mass balance, which may not be conserved. Serial hybrid models contain feature learning where the data-driven model predicts a subprocess of the mechanistic model (Gaublomme et al., 2022) and physics-based preprocessing for the data-driven model (e.g. Wärff et al., 2025).. The last architecture are universal differential equations that are on the rise as they allow for explainable AI techniques to enhance model transparency and trust (e.g. Quaghebeur et al., 2025; Zou et al., 2023;.

Looking into other fields, the core principles of hybrid modelling resonate with developments in the field of scientific machine learning (SciML). SciML resides at the intersection of statistics,

physical modelling, and machine learning and its central aim is to integrate scientific knowledge into data-driven methods in order to reduce data requirements, improve generalisation, and accelerate the training and deployment of machine learning models (Baker et al., 2019). Importantly, SciML extends beyond the scope of hybrid modelling: while hybrid approaches explicitly combine first-principle models with data-driven components, SciML emphasises embedding scientific constraints and domain knowledge directly into the learning process. This broader perspective encompasses techniques such as physics-informed neural networks, surrogate modelling for complex simulations, and equation discovery (e.g. through symbolic regression) from experimental data. Although many of these approaches have already transformed fields, such as climate science and materials engineering, their application in the water sector, particularly for water quality applications, remains limited. These underexplored aspects of SciML could further enable the development of high-fidelity models that capture complex water system dynamics, accelerate simulations within digital twin environments, and uncover new scientific insights from the data streams generated by modern monitoring technologies. As hybrid modelling, SciML can be tuned to deal with sparse data situations that are still prevalent in the environmental sector for parameters of interest.

The recent advent of large language models (LLMs) has opened new pathways for knowledge extraction, synthesis, and decision support in the water sector. LLMs can assist with information synthesis, technical writing, and decision support. A few published examples showing applications of currently available generative pre-trained transformers (GPT) for knowledge extraction and synthesis in water applications are available, such as Nie and Liu (2025). However, achieving domain-specific problem solving requires fine-tuning or retrieval-augmented generation (RAG) of pre-trained models, as shown in Zhu et al. (2024). The domain-specific LLMs are expected to support various applications in the water sector, such as technical information retrieval, real-time operational decision support, and automated reporting/log generation.

CHALLENGES TO THE WIDER APPLICATION OF DATA-DRIVEN AND HYBRID MODELS

A multitude of challenges exist when it comes to data-driven and hybrid models. Among them cyber security is for sure one (Vanrolleghem et al., 2025). We want to hightlight here a few more.

1. Data scarcity and model generalisation.
Many data-driven approaches face constraints due to limited high-quality data, narrowing operational variability and reducing model generalisation. The quantity is limited by monetary costs for sensor hardware and maintenance, the quality by sensor fouling, and incomplete metadata. Data-driven models often perform well under seen conditions but fail to extrapolate. There is a growing need for systematic comparison of algorithms in terms of inductive biases and extrapolation capacity in different water and wastewater applications. Using synthetic or simulated data for the development of data-driven models offers promise, but their real-world transfer remains limited by the simulation–reality gap (Zhu et al., 2023).

2. Purpose alignment and evaluation metrics.
In water and wastewater systems, the same operational challenge can often be formulated in multiple ways – each leading to fundamentally different modelling strategies and outcomes. The choice of performance metrics must reflect operational objectives. Inappropriate metric selection can result in inconsistencies between metric outcomes and actual system behaviour. An example of a known issue is that regression metrics can be weakly correlated resulting in contradictory rankings of model performance, hence including robustness, interpretability, and complexity is suggested (Khalil et al., 2023) Furthermore, certain metrics (e.g. mean absolute percentage error, MAPE) penalise over- and underestimation asymmetrically, complicating the interpretation (Tofallis, 2015). Therefore, framing of objectives and metrics requires integrative knowledge of both process engineering and modern ML – highlighting the importance of interdisciplinary collaboration.

3. Causality vs correlation.
ML captures associations, not necessarily causation. For decision-making purposes, relying on correlated surrogate inputs (e.g. downstream effects of ammonia) may yield accurate predictions but fail to identify actionable interventions (Pearl and Mackenzie, 2019). Integrating causal inference tools and domain-knowledge constraints is essential for trustworthy, decision-oriented water ML.

4. Benchmarking and alignment.
A unified benchmarking system is still missing, limiting the comparability of results and therefore decision making based on them; extending existing benchmark models (such as BSM1) and developing benchmarking datasets to evaluate different hybrid and data-driven modelling strategies could provide the transparency needed for cross-comparison and regulatory confidence.

In this context, the IWA working group on hybrid modelling has launched an initiative to collect, review, and publish hybrid modelling examples: https://gitlab.com/hm_wg/examples. Aligning these challenges with the IWA initiatives on digital twin standardisation and data governance is essential. Hybrid modelling requires a wide range of skills that are not present in most environmental engineering courses and should be considered for inclusion in university curricula.

Harnessing diverse modelling frameworks

Example: soft sensors

Recent advances in AI and the promise of data-driven models is putting the data-collection in the spotlight. In this context, soft sensors – i.e. virtual sensors combining physical measurements with models implemented in software – have gained significant traction. For instance, data-driven soft sensors are increasingly used in digital twin applications (Haimi et al., 2026), while hybrid and physics-informed approaches support the monitoring of complex contaminants in sewer overflows (Waldner et al., 2025). At the same time, mechanistic perspectives remain essential to ensure robustness and interpretability. A novel approach for soft-sensor design is dynamical systems analysis where dynamics are systematically explored to increase the soft-sensor robustness and fault tolerance (Schneider et al., 2026).

Example: N_2O

Nitrous oxide (N_2O) is the most consequential direct greenhouse gas emitted from WRRFs. Short-lived spikes that are still poorly understood often dominate annual inventories, with contributions up to 80% of Scope 1 impacts in some facilities (Song et al., 2024). N_2O mitigation remains challenging because emissions arise from complex interactions among biochemical, physicochemical, and mass transfer processes that are difficult to diagnose, predict, and control at full scale (Zhao et al., 2024). Against this backdrop, N_2O modelling has become an area of intense research and development interest.

Mechanistic N_2O models currently represent nitrifier nitrification, nitrifier denitrification, heterotrophic denitrification, and, in some cases, abiotic NH_2OH reactions well (Khalil et al., 2024). The full-scale applications of these models remain limited by structural and practical identifiability issues (Vasilaki et al., 2019). Additional uncertainty in gas–liquid transfer, directly propagates into emission estimates (Baeten et al., 2020). Computational fluid dynamics (CFD)–kinetics integration is expanding to capture these uncertainties (Daneshgar et al., 2024).

High-frequency WRRF datasets have accelerated the adoption of supervised ML to capture process dynamics and identify key features correlating with emissions (Hwangbo et al., 2021; Khalil et al., 2023). Extraopolation and interpretability constraints position ML applications as a complementary layer providing responsiveness, anomaly detection, and short-term forecasting. Data-driven surrogate models are showing potential for real-time use of computationally demanding CFD models.

Hybrid mechanistic–ML frameworks are rapidly advancing (Li et al., 2022). Together, this ecosystem of modelling approaches enhances our ability to diagnose, predict, and mitigate N_2O emissions, underscoring the value of methodological diversity in tackling such a multifaceted challenge.

The need for good modelling practices

As modelling applications and architectures evolve in response to new drivers in the water industry, the need for good modelling practices (GMPs) becomes increasingly critical. Guidance is required not only for model development but also for model selection, ensuring that practitioners choose architectures suited to their objectives and data environments. Although data-driven methods often follow a standard workflow, the process can quickly become complex due to challenges in data quality and quantity. Robust and accurate models, therefore, depend on GMPs that help avoid common pitfalls across the entire pipeline: data collection, cleaning, feature engineering, model development, interpretation, and causality analysis. Zhu et al. (2023) showed that over half of the reviewed supervised ML studies overlooked critical steps, with recurring issues such as temporal data leakage, improper preprocessing, feature scaling errors, inadequate hyperparameter optimisation, and weak model explanation. Similarly, Tedoldi et al. (2025) highlighted widespread misuses in statistical learning – including neglect of model assumptions, overfitting, misinterpreting correlations, and ignoring uncertainty – underscoring the need for transparency, diagnostic checks, and collaboration between data scientists and domain experts. While supervised ML practices are gradually being codified, emergent methods such as generative AI and reinforcement learning (RL) lack established guidelines for water sector applications. Developing GMPs for these approaches will be essential to ensure responsible and effective deployment.

For hybrid models, GMPs are needed with respect to the selection of optimal architectures or calibration/validation strategies. Identifiability deserves special attention: hybrid models may compensate for missing dynamics in ways that obscure true mechanisms, and traditional techniques may fail to detect this. As modelling transitions into long-term decision support and real-time applications, GMPs must also expand to cover uncertainty analysis and model ownership (Belia et al., 2021). This work will be carried forward into a practical framework by the newly established DOUT2.0 working group.

Finally, GMPs should recognise that models are increasingly treated as long-term assets. WRRF owners often retain models from past projects, reuse them, and share them with external engineers. Ownership therefore extends beyond initial development to include version control, continual validation, risk management, and periodic recalibration or redevelopment. Documentation of assumptions, uncertainties, and decisions is vital to ensure future users understand the model's context and quality, and to support ongoing validation.

References

Ahmed, F., Tscharke, B., O'Brien, J. W., Cabot, P. J., Hall, W. D., Mueller, J. F., & Thomas, K. V. (2020a). Can wastewater analysis be used as a tool to assess the burden of pain treatment within a population? *Environmental Research, 188*, 109769. https://doi.org/10.1016/j.envres.2020.109769

Ahmed, W., Angel, N., Edson, J., Bibby, K., Bivins, A., O'Brien, J. W., Choi, P. M., Kitajima, M., Simpson, S. L., Li, J., Tscharke, B., Verhagen, R., Smith, W. J., Zaugg, J., Dierens, L., Hugenholtz, P., Thomas, K. V., & Mueller, J. F. (2020b). First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: A proof of concept for the wastewater surveillance of COVID-19 in the community. *Science of the Total Environment*, *728*, 138764. https://doi.org/10.1016/j.scitotenv.2020.138764

Alves, A., Van Opstal, C., Keijzer, N., Sutton, N., & Chen, W. (2024). Planning the multifunctionality of nature-based solutions in urban spaces. *Cities, 146*, 104751. https://doi.org/10.1016/j.cities.2023.104751

Alvi, M., Batstone, D., Mbamba, C.K., Keymer, P., French, T., Ward, A., Dwyer, J. and Cardell-Oliver, R. (2023). Deep learning in wastewater treatment: a critical review. *Water Researc*h, *245*, 120518, https://doi.org/10.1016/j.watres.2023.120518.

Bach, P. M., Kuller, M., McCarthy, D. T., & Deletic, A. (2020). A spatial planning-support system for generating decentralised urban stormwater management schemes. *Science of the Total Environment, 726*, 138282. https://doi.org/10.1016/j.scitotenv.2020.138282

Bahramian, M., Dereli, R. K., Zhao, W., Giberti, M., & Casey, E. (2023). Data to intelligence: The role of data-driven models in wastewater treatment. *Expert Systems with Applications, 217*, 119453. https://doi.org/10.1016/j.eswa.2022.119453

Baeten, J. E., Van Loosdrecht, M. C., & Volcke, E. I. (2020). When and why do gradients of the gas phase composition and pressure affect liquid-gas transfer? *Water Research, 178*, 115844. https://doi.org/10.1016/j.watres.2020.115844

Baker, N., Alexander, F., Bremer, T., Hagberg, A., Kevrekidis, Y., Najm, H., Parashar, M., Patra, A., Sethian, J., Wild, S., Willcox, K., & Lee, S. (2019). *Workshop Report on Basic Research Needs for Scientific Machine Learning: Core Technologies for Artificial Intelligence*. https://doi.org/10.2172/1478744

Batstone, D. J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V., Pavlostathis, S. G., Rozzi, A., Sanders, W.T.M., Siegrist, H., & Vavilin, V. A. (2002). The IWA anaerobic digestion model no 1 (ADM1). *Water Science and Technology, 45*(10), 65–73. https://doi.org/10.2166/wst.2002.0292

Batstone, D. J., & Flores-Alsina, X. (Eds.). (2022). *Generalised Physicochemical Model (PCM) for Wastewater Processes*. IWA Publishing. https://doi.org/10.2166/9781780409832

Baumgartner, S., Salvisberg, M., Schmidhalter, P., Julian, T. R., Ort, C., & Singer, H. (2025). Insights into respiratory illness at the population level through parallel analysis of pharmaceutical and viral markers in wastewater. *Nature Water, 3*(5), 580–589. https://doi.org/10.1038/s44221-025-00437-4

Belia, E., Benedetti, L., Johnson, B., Murthy, S., Neumann, M. B., Vanrolleghem, P. A., & Weijers, S. (2021). *Uncertainty in wastewater treatment design and operation: addressing current practices and future directions* (IWA Scientific and Technical Report No. 21). London: IWA Publishing. DOI: https://doi.org/10.2166/9781780401034

Borzooei S., Scabini L., Miranda G., Daneshgar S., Deblieck L., Bruno O., De Langhe P., De Baets B., Nopens I., Torfs E. (2024). Evaluation of activated sludge settling characteristics from microscopy images with deep convolutional neural networks and transfer learning. *Journal of Water Process Engineering*, *64*, 105692.

Bosch, L. M., Pueyo-Ros, J., Comas-Cufí, M., Saldaña, J., Ripoll, J., Calle, E., Casas, P. F. I., Subirana, J. G. I., Borrego, C. M., & Corominas, L. (2024). Watching the guards: A data-driven method to trigger warnings in national wastewater surveillance networks. *Journal of Water and Health*, *22*(7), 1209–1221. https://doi.org/10.2166/wh.2024.043

Brewster, E. T., Mehta, C. M., Radjenovic, J., & Batstone, D. J. (2016). A mechanistic model for electrochemical nutrient recovery systems. *Water Research, 94*, 176–186. https://doi.org/10.1016/j.watres.2016.02.032

Carecci, D., Catenacci, A., Rossi, S., Casagli, F., Ferretti, G., Leva, A., & Ficara, E. (2024). A plant-wide modelling framework to describe microalgae growth on liquid digestate in agro-zootechnical biomethane plants. *Chemical Engineering Journal*, *485*, 149981. https://doi.org/10.1016/j.cej.2024.149981

Casagli, F., Turolla, A., Batstone, D. J., Capson-Tojo, G., Ficara, E., García, J., González-Flo, E., Laurent, J., Lorenz, T., Pierrelée, M., Plósz, B. Gy., Da Silva, G. H. R., Robles, Á., Rossi, S., Rueda-Hernández, E., Stegemüller, L., Steyer, J.-P., Bernard, O., & Valverde-Pérez, B. (2025). Modelling challenges to unlock the power of phototrophic systems for wastewater valorization. *Biotechnology Advances, 85*, 108709. https://doi.org/10.1016/j.biotechadv.2025.108709

Centre TFNIG. (2019). First Nations data sovereignty in Canada. *Statistical Journal of the IAOS, 35*(1), 47–69. https://doi.org/10.3233/sji-180478

Chen, K., Wang, H., Valverde-Pérez, B., Zhai, S., Vezzaro, L., & Wang, A. (2021). Optimal control towards sustainable wastewater treatment plants based on multi-agent reinforcement learning. *Chemosphere*, 279, 130498 . https://doi.org/10.1016/j.chemosphere.2021.130498

Croll, H. C., Ikuma, K., Ong, S. K., & Sarkar, S. (2024). Unified control of diverse actions in a wastewater treatment activated sludge system using reinforcement learning for multi-objective optimization. *Water Research*, 263, 122179.

Cluzel, N., Courbariaux, M., Wang, S., Moulin, L., Wurtzer, S., Bertrand, I., Laurent, K., Monfort, P., Gantzer, C., Guyader, S. L., Boni, M., Mouchel, J., Maréchal, V., Nuel, G., & Maday, Y. (2022). A nationwide indicator to smooth and normalize heterogeneous SARS-CoV-2 RNA data in wastewater. *Environment International, 158*, 106998. https://doi.org/10.1016/j.envint.2021.106998

Cohen-Shacham, E., Janzen, C., Maginnis, S., & Walters, G. (Eds.). (2016). *Nature-based solutions to address global societal challenges.* IUCN. https://doi.org/10.2305/IUCN.CH.2016.13.en

Corominas, Ll., M. Garrido-Baserba, K. Villez, G. Olsson, U. Cortés, and M. Poch. Transforming data into knowledge for improved wastewater treatment operation: a critical review of techniques. *Environmental Modelling & Software* 106, 89–103. https://doi.org/10.1016/j.envsoft.2017.11.023.

Courbariaux, M., Cluzel, N., Wang, S., Maréchal, V., Moulin, L., Wurtzer, S., Mouchel, J., Maday, Y., & Nuel, G. (2022). A flexible smoother adapted to censored data with outliers and its application to SARS-CoV-2 Monitoring in Wastewater. *Frontiers in Applied Mathematics and Statistics, 8*. https://doi.org/10.3389/fams.2022.836349

Daneshgar S., Amerlinck Y., Amaral A., De Mulder C., Di Nisio A., Bellandi G., Gori R., Caretti C., Ducci I., Rehman U., Porro J., Nopens I., Torfs E. (2024). An innovative model-based protocol for minimisation of greenhouse gas (GHG) emissions in WRRFs. *Chemical Engineering Journal*, 483, 148327.

D'Aoust, P. M. (2025). Wastewater surveillance requires ethical use. *Science, 389*(6766), 1194. https://doi.org/10.1126/science.adq6656

Dudley, J., Dillon, G., & Rietveld, L. C. (2008). Water treatment simulators. *Journal of Water Supply Research and Technology—AQUA, 57*(1), 13–21. https://doi.org/10.2166/aqua.2008.096

Elduayen-Echave, B., & Ayesa, E. (2025). DriWM®: A comprehensive drinking water modelling framework for integral simulation of drinking water treatment plants. *Journal of Water Process Engineering, 76*, 108274. https://doi.org/10.1016/j.jwpe.2025.108274

European Parliament & Council. (2020). *Directive (EU) 2020/2184 of the European Parliament and of the Council on the quality of water intended for human consumption* (Recast). Official Journal of the European Union. https://data.europa.eu/eli/dir/2020/2184/oj

Gaublomme D., Quaghebeur W, Van Droogenbroeck A., Vanoppen M., De Gusseme B., Verliefde A., Nopens I., Torfs E. (2023). A hybrid modelling approach for reverse osmosis processes including fouling. *Desalination, 564*, 116756. https://doi.org/10.1016/j.desal.2023.116756

Gholipour, S., Shamsizadeh, Z., Halabowski, D., Gwenzi, W., & Nikaeen, M. (2024). Combating antibiotic resistance using wastewater surveillance: Significance, applications, challenges, and future directions. *Science of the Total Environment, 908*, 168056. https://doi.org/10.1016/j.scitotenv.2023.168056

Huisman, J. S., Scire, J., Caduff, L., Fernandez-Cassi, X., Ganesanandamoorthy, P., Kull, A., Scheidegger, A., Stachler, E., Boehm, A. B., Hughes, B., Knudson, A., Topol, A., Wigginton, K. R., Wolfe, M. K., Kohn, T., Ort, C., Stadler, T., & Julian, T. R. (2022). Wastewater-based estimation of the effective reproductive number of SARS-CoV-2. *Environmental Health Perspectives, 130*(5), 57011. https://doi.org/10.1289/ehp10050

Guillaume-Ruty, S.H. (2025). *Model hybridisation for reliable decision-making*. Doctoral dissertation, INSA Lyon, University of Girona.

Haimi, H., Awaitey, A., Kiran, A., Larsson, T., Blomberg, K., Elvander, F., Petäjä, E., Mulas, M., Sahlstedt, K., Mikola, A. (2025). Integrating data-driven models and process expertise in soft-sensor design for a wastewater treatment digital twin application". *Water Science and Technology 92*, (9), 1308–27. https://doi.org/10.2166/wst.2025.154.

Henze, M., Gujer, W., Mono, T., & Van Loosdrecht, M. C. M. (2000). *Activated sludge models ASM1, ASM2, ASM2d and ASM3* (Scientific and Technical Report No. 9). IWA Publishing. https://doi.org/10.2166/9781780402369

Hernández-del-Olmo, F., Gaudioso, E., Duro, N., Dormido, R., & Gorrotxategi, M. (2012). Autonomous adaptive and active tuning up of the dissolved oxygen setpoint in a wastewater treatment plant using reinforcement learning. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews, 42*(5), 768–774.

Hörnschemeyer, B., Henrichs, M., & Uhl, M. (2021). SWMM-UrbanEVA: A Model for the Evapotranspiration of Urban Vegetation. *Water, 13*(2), 243. https://doi.org/10.3390/w13020243

Hwangbo, S., Al, R., Chen, X., & Sin, G. (2021). Integrated model for understanding N_2O emissions from wastewater treatment plants: a deep learning approach. *Environmental Science & Technology, 55*(3), 2143–2151. https://doi.org/10.1021/acs.est.0c05231

Istenič, D., Bodík, I., Merisaar, M., Gajewska, M., Šereš, M., & Griessler Bulc, T. (2023). Challenges and perspectives of nature-based wastewater treatment and reuse in rural areas of central and eastern Europe. *Sustainability, 15*(10), 8145. https://doi.org/10.3390/su15108145

Jensen, T. B., Anand, M., Batstone, D., & Kofoed, M. V. W. (2025). Here comes the sun: intermittent operation of hydrogen-based in situ biomethanation at pilot-scale. *Applied Energy, 401*, 126601. https://doi.org/10.1016/j.apenergy.2025.126601

Jiang, Y., Hebly, M., Kleerebezem, R., Muyzer, G., & van Loosdrecht, M. C. M. (2011). Metabolic modeling of mixed substrate uptake for polyhydroxyalkanoate (PHA) production. *Water Research*, 45(3), 1309–1321. https://doi.org/10.1016/j.watres.2010.10.009

Joseph-Duran, B., Serra-Compte, A., Sàrrias, M., Gonzalez, S., López, D., Prats, C., Català, M., Alvarez-Lacalle, E., Alonso, S., & Arnaldos, M. (2022). Assessing wastewater-based epidemiology for the prediction of SARS-CoV-2 incidence in Catalonia. *Scientific Reports, 12*(1), 15073. https://doi.org/10.1038/s41598-022-18518-9

Kadlec, R. H., & Wallace, S. (2009). *Treatment wetlands* (pp. 267–347). CRC Press.

Khalil, M., AlSayed, A., Liu, Y., & Vanrolleghem, P. A. (2023). Machine learning for modeling N_2O emissions from wastewater treatment plants: Aligning model performance, complexity, and interpretability. *Water Research, 245*, 120667. https://doi.org/10.1016/j.watres.2023.120667

Khalil, M., AlSayed, A., Elsayed, A., Zaghloul, M. S., Bell, K. Y., Al-Omari, A., Kakar, F. L., Houweling, D., Santoro, D., Porro, J., & Elbeshbishy, E. (2024). Advances in GHG emissions modelling for WRRFs: From state-of-the-art methods to full-scale applications. *Chemical Engineering Journal, 494*, 153053. https://doi.org/10.1016/j.cej.2024.153053

Langergraber, G., Rousseau, D. P. L., García, J., & Mena, J. (2009). CWM1: a general model to describe biokinetic processes in subsurface flow constructed wetlands. *Water Science & Technology, 59*(9), 1687–1697. https://doi.org/10.2166/wst.2009.131

Li, F., & Vanrolleghem, P. A. (2022). An influent generator for WRRF design and operation based on a recurrent neural network with multi-objective optimization using a genetic algorithm. *Water Science & Technology, 85*(5), 1444–1453. https://doi.org/10.2166/wst.2022.048

Li, K., Duan, H., Liu, L., Qiu, R., Van Den Akker, B., Ni, B., Chen, T., Yin, H., Yuan, Z., & Ye, L. (2022). An integrated first principal and deep learning approach for modeling nitrous oxide emissions from wastewater treatment plants. *Environmental Science & Technology, 56*(4), 2816–2826. https://doi.org/10.1021/acs.est.1c05020

Lippera, M. C., Khurelbaatar, G., Despot, D., Kouyi, G. L., Rizzo, A., & Friesen, J. (2025). Spatial-economic scenarios to increase resilience to urban flooding. *Water Research X, 26*, 100284. https://doi.org/10.1016/j.wroa.2024.100284

Lizarralde, I., Fernández-Arévalo, T., Manas, A., Ayesa, E., & Grau, P. (2019). Model-based optimization of phosphorus management strategies in Sur WWTP, Madrid. *Water Research, 153*, 39–52. https://doi.org/10.1016/j.watres.2018.12.056

McCall, A., Bade, R., Kinyua, J., Lai, F.Y., Thai, P.K., Covaci, A. Bijlsma, L., van Nuijs, A, Ort, C. (2016). Critical review on the stability of illicit drugs in sewers and wastewater samples". *Water Research 88*:,933–947. https://doi.org/10.1016/j.watres.2015.10.040.

Maere, T., Therrien, J. D., & Vanrolleghem, P. A. (2022). *Normalization practices for SARS-CoV-2 data in wastewater-based epidemiology.* National Collaborating Centre for Infectious Diseases, Public Health Agency of Canada.

Makarigakis, A. K., & Jimenez-Cisneros, B. E. (2019). UNESCO's contribution to face global water challenges. *Water, 11*(2), 388. https://doi.org/10.3390/w11020388

Mannina, G., Rebouças, T. F., Cosenza, A., Sànchez-Marrè, M., & Gibert, K. (2019). Decision support systems (DSS) for wastewater treatment plants – A review of the state of the art. *Bioresource Technology, 290*, 121814. https://doi.org/10.1016/j.biortech.2019.121814

Mannina, G., Ni, B., Makinia, J., Harmand, J., Alliet, M., Brepols, C., Ruano, M. V., Robles, A., Heran, M., Gulhan, H., Rodriguez-Roda, I., & Comas, J. (2023). Biological processes modelling for MBR systems: A review of the state-of-the-art focusing on SMP and EPS. *Water Research, 242*, 120275. https://doi.org/10.1016/j.watres.2023.120275

Morvan, M., Lo Jacomo, A., Souque, C., Wade, M. J., Hoffmann, T., Pouwels, K., Lilley, C., Singer, A. C., Porter, J., Evens, N. P., Walker, D. I., Bunce, J. T., Engeli, A., Grimsley, J., O'Reilly, K. M., & Danon, L. (2022). An analysis of 45 large-scale wastewater sites in England to estimate SARS-CoV-2 community prevalence. *Nature Communications, 13*(1), 4313. https://doi.org/10.1038/s41467-022-31753-y

Munk, P., Brinch, C., & Aarestrup, F. M. (2025). Resistance genes are not like chemical pollutants and surveillance of them should reflect that. *Future Microbiology, 20*(5), 379–381. https://doi.org/10.1080/17460913.2025.2476880

Nguyen, X. C., Nguyen, T. T. H., Le, Q. V., Le, P. C., Srivastav, A. L., Pham, Q. B., Nguyen, P. M., La, D. D., Rene, E. R., Ngo, H. H., Chang, S. W., & Nguyen, D. D. (2022). Developing a new approach for design support of subsurface constructed wetland using machine learning algorithms. *Journal of Environmental Management, 301*, 113868. https://doi.org/10.1016/j.jenvman.2021.113868

Nie, Q., & Liu, T. (2025). Large language models: Tools for new environmental decision-making. *Journal of Environmental Management, 375*, 124373. https://doi.org/10.1016/j.jenvman.2025.124373

Panduro, T. E., & Veie, K. L. (2013). Classification and valuation of urban green spaces—A hedonic house price valuation. *Landscape and Urban Planning, 120*, 119–128. https://doi.org/10.1016/j.landurbplan.2013.08.009

Pearl, J., & Mackenzie, D. (2019). *The book of why*. Penguin Books.

Prodanovic, V., Bach, P. M., & Stojkovic, M. (2024). Urban nature-based solutions planning for biodiversity outcomes: human, ecological, and artificial intelligence perspectives. *Urban Ecosystems, 27*(5), 1795–1806. https://doi.org/10.1007/s11252-024-01558-6

Pueyo-Ros, J., Mendoza, E., Buttiglieri, G., & Comas, J. (2025). Nat4Wat: a co-developed decision-support system for resilient urban water management with nature-based solutions. *Environmental Modelling & Software, 196*, 106797. https://doi.org/10.1016/j.envsoft.2025.106797

Qu, W., Zheng, W., Wang, S., & Wang, Y. (2012). China's new national standard for drinking water takes effect. *The Lancet, 380*(9853), e8. https://doi.org/10.1016/s0140-6736(12)61884-4

Quaghebeur, W., Torfs, E., Khalil, M., Nopens, I., & De Baets, B. (2025). Uncovering unknown dynamics in water resource recovery facilities with neural differential equations and Shapley values. *Journal of Water Process Engineering, 70*, 106856

Rauch, W., Schenk, H., Insam, H., Markt, R., & Kreuzinger, N. (2022). Data modelling recipes for SARS-CoV-2 wastewater-based epidemiology. *Environmental Research, 214*(1), 113809. https://doi.org/10.1016/j.envres.2022.113809

Riquelme, M. V. P., Garner, E., Gupta, S., Metch, J., Zhu, N., Blair, M. F., Arango-Argoty, G., Maile-Moskowitz, A., Li, A., Flach, C., Aga, D. S., Nambi, I. M., Larsson, D. G. J., Bürgmann, H., Zhang, T., Pruden, A., & Vikesland, P. J. (2022). Demonstrating a comprehensive wastewater-based surveillance approach that differentiates globally sourced resistomes. *Environmental Science & Technology, 56*(21), 14982–14993. https://doi.org/10.1021/acs.est.1c08673

Rosse, C., Forquet, N., Lombard-Latune, R., Nivala, J., Castebrunet, H., & Molle, P. (2023). Quels outils et méthodes décisionnels pour une gestion décentralisée des eaux urbaines par des solutions fondées sur la nature : une revue bibliographique. T*echniques Sciences Méthodes, 9*, 123–147. https://doi.org/10.36904/tsm/202309123

Samsó, R., García, J., Molle, P., & Forquet, N. (2016). Modelling bioclogging in variably saturated porous media and the interactions between surface/subsurface flows: Application to constructed wetlands. *Journal of Environmental Management, 165*, 271–279. https://doi.org/10.1016/j.jenvman.2015.09.045

Schneider, M. Y., Quaghebeur, W., Borzooei, S., Froemelt, A., Li, F., Saagi, R., Wade, M. J., Zhu, J., & Torfs, E. (2022). Hybrid modelling of water resource recovery facilities: status and opportunities. *Water Science & Technology, 85*(9), 2503–2524. https://doi.org/10.2166/wst.2022.115

Schneider, M. Y., Torfs, E., Carbajal, J. P. (2026). Unveiling the immoral ramp feature of dissolved oxygen signals with dynamical systems analysis: perspectives for robust soft-sensor development. *Scientific Reports 16* (1), 15414. https://doi.org/10.1038/s41598-026-43885-y.

Senta, I., Rodríguez-Mozaz, S., Corominas, L., & Petrovic, M. (2020). Wastewater-based epidemiology to assess human exposure to personal care and household products – A review of biomarkers, analytical methods, and applications. *Trends in Environmental Analytical Chemistry, 28*, e00103. https://doi.org/10.1016/j.teac.2020.e00103

Serrao, M., Jauzein, V., Juran, I., Tassin, B., & Vanrolleghem, P. (2024). Hybrid modelling of nitrogen removal by biofiltration using high-frequent operational data. *Water Science & Technology, 90*(5), 1416–1432. https://doi.org/10.2166/wst.2024.293

Seshan, S., Poinapen, J., Zandvoort, M. H., Van Lier, J. B., & Kapelan, Z. (2024). Limitations of a biokinetic model to predict the seasonal variations of nitrous oxide emissions from a full-scale wastewater treatment plant. *Science of the Total Environment, 917*, 170370. https://doi.org/10.1016/j.scitotenv.2024.170370

Shoener, B. D., Schramm, S. M., Béline, F., Bernard, O., Martínez, C., Plósz, B. G., Snowling, S., Steyer, J., Valverde-Pérez, B., Wágner, D., & Guest, J. S. (2019). Microalgae and cyanobacteria modeling in water resource recovery facilities: A critical review. *Water Research X,* 2, 100024. https://doi.org/10.1016/j.wroa.2018.100024

Solon, K., Flores-Alsina, X., Mbamba, C. K., Ikumi, D., Volcke, E.I.P., Vaneeckhaute, C., Ekama, G., Vanrolleghem, P.A., Batstone, D.J., Gernaey, K.V., & Jeppsson, U. (2017). Plant-wide modelling of phosphorus transformations in wastewater treatment systems: Impacts of control and operational strategies. *Water Research, 113*, 97–110. https://doi.org/10.1016/j.watres.2017.02.007

Song, C., J.-J. Zhu, J. L. Willis, D. P. Moore, M. A. Zondlo, & Z. J. Ren. (2024). Oversimplification and misestimation of nitrous oxide emissions from wastewater treatment plants. *Nature Sustainability, 7*(10), 1348–1358. https://doi.org/10.1038/s41893-024-01420-9

Tafti, A. D.i, Houweling, D., Perron, J.M. et al. (2024). Towards a modelling framework for nature-based solutions in wastewater treatment. *Water Science and Technology 90*(3), 758–76. https://doi.org/10.2166/wst.2024.235.

Tallis, H.T., Ricketts, T., Guerry, A.D., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., & Aukema, J. (2011). *InVEST 2.1 beta user's guide*. The Natural Capital Project.

Tedoldi, D., Kim, B., Sandoval, S., Forquet, N., & Tassin, B. (2025). Position paper: Common mistakes and solutions for a better use of correlation- and regression-based approaches in environmental sciences. *Environmental Modelling & Software, 192*, 106526. https://doi.org/10.1016/j.envsoft.2025.106526

Therrien, J. D., Thomson, M., Maere, T., Manuel, D., & Vanrolleghem, P. A. (2022). Developing an open-source, relational data model for recording SARS-CoV-2 signals across multiple sewersheds. In: *Proceedings of the 10th international Conference on Sewer Processes and Networks*. Graz, Austria.

Tik, S., Lopez Vega, L. L., Tan, Y., Noël, L. P., Maere, T., Celikkol, S., Meng, Q., Frigon, D., Poirier-Gagnon, S., Rioux, M. D., Hajj-Mohammad, M., Dorner, S., Nourbakhsh, S., Yusuf, W., Champredon, D., Fazil, A., & Vanrolleghem, P. A. (2024). Development of a phenomenological sewer water quality model to enhance wastewater-based epidemiology. In: P*roceedings of the 16th IWA International Conference on Urban Drainage (ICUD2024)*. Delft, The Netherlands.

Tofallis, C. (2015). A better measure of relative prediction accuracy for model selection and model estimation. *Journal of the Operational Research Society, 66*(8), 1352–1362. https://doi.org/10.1057/jors.2014.103

U.S. Environmental Protection Agency. (2009). *National primary drinking water guidelines* (EPA 816-F-09-004). https://www.regulations.gov/document/EPA-HQ-OPPT-2009-0477-0003

Vaneeckhaute, C., Claeys, F.H.A., Tack, F.M.G., Meers, E., Belia, E., & Vanrolleghem, P.A. (2018). Development, implementation, and validation of a generic nutrient recovery model (NRM) library. *Environmental Modelling & Software, 99,* 170–209. https://doi.org/10.1016/j.envsoft.2017.09.002

Vanrolleghem PA, Khalil M, Serrao M, Sparks J, Therrien JD (2025). Machine learning in wastewater: opportunities and challenges - “not everything is a nail!”. *Current Opinion in Biotechnology, 93*,103271. doi: 10.1016/j.copbio.2025.103271

Vasilaki, V., Massara, T.M., Stanchev, P., Fatone, F., & Katsou, E. (2019). A decade of nitrous oxide (N_2O) monitoring in full-scale wastewater treatment processes: A critical review. *Water Research, 161*, 392–412. https://doi.org/10.1016/j.watres.2019.04.022

Von Stosch, M., Oliveira, R., Peres, J., & De Azevedo, S. F. (2014). Hybrid semi-parametric modeling in process systems engineering: Past, present and future. *Computers & Chemical Engineering, 60*, 86–101. https://doi.org/10.1016/j.compchemeng.2013.08.008

Wágner, D. S., Valverde-Pérez, B., Sæbø, M., De La Sotilla, M. B., Van Wagenen, J., Smets, B. F., & Plósz, B. G. (2016). Towards a consensus-based biokinetic model for green microalgae – The ASM-A. *Water Research, 103*, 485–499. https://doi.org/10.1016/j.watres.2016.07.026

Waldner, L., Furrer, V., Lechevallier, P., Maire, F., Singer, H., Mutzner, L. (2025). Exploring online sensor parameters as proxies for polar organic chemicals—an innovative approach for combined sewer overflow monitoring. *PLOS ONE 20*(10), e0333173. https://doi.org/10.1371/journal.pone.0333173.

Wang, X., Carvalho, G., Reis, M. A. M., & Oehmen, A. (2018). Metabolic modeling of the substrate competition among multiple VFAs for PHA production by mixed microbial cultures. J*ournal of Biotechnology*, 280, 62–69. https://doi.org/10.1016/j.jbiotec.2018.06.342

Wärff, C., Carlsson, B., Arnell, M., Micolucci, F., Samuelsson, O., Jeppsson. U. (2025) Using a hybrid modelling approach for high time-resolution prediction of influent orthophosphate load in a water resource recovery facility. *Water Research, 286,* 124176, https://doi.org/10.1016/j.watres.2025.124176.

Zahra, S. A., Persiani, R., Dueholm, M. K., Van Loosdrecht, M., Nielsen, P. H., Seviour, T. W., & Lin, Y. (2024). Rethinking characterization, application, and importance of extracellular polymeric substances in water technologies. *Current Opinion in Biotechnology, 89*, 103192. https://doi.org/10.1016/j.copbio.2024.103192

Zarei, S., Salimi, Y., Repo, E., Daglioglu, N., Safaei, Z., Güzel, E., & Asadi, A. (2020). A global systematic review and meta-analysis on illicit drug consumption rate through wastewater-based epidemiology. *Environmental Science and Pollution Research, 27*(29), 36037–36051. https://doi.org/10.1007/s11356-020-09818-6

Zhao, Y., Du, L.-L., Hu, B., Lin, H.-Y., Liang, B., Song, Y.-P., Wang, Y.-Q., Wang, H.-W., Li, P.-F., Wang, A.-J., & Wang, H.-C. (2024). Impact of influent characteristics and operational parameters on nitrous oxide emissions in wastewater treatment: Strategies for mitigation and microbial insights. *Current Research in Biotechnology, 7*, 100207. https://doi.org/10.1016/j.crbiot.2024.100207

Zhu, J.-J., Yang, M., & Ren, Z. J. (2023). Machine learning in environmental research: common pitfalls and best practices. *Environmental Science & Technology, 57*(46), 17671-17689. https://doi.org/10.1021/acs.est.3c00026

Zhu, J.-J., Yang, M., Jiang, J., Bai, Y., Chen, D., & Ren, Z. J. (2024). Enabling GPTs for expert-level environmental engineering question answering. *Environmental Science & Technology Letters, 11*(12), 1327–1333. https://doi.org/10.1021/acs.estlett.4c00665

Zou, X., Guo, H., Jiang, C., Nguyen, D. V., Chen, G., & Wu, D. (2023). Physics-informed neural network-based serial hybrid model capturing the hidden kinetics for sulfur-driven autotrophic denitrification process. *Water Research, 243*, 120331. https://doi.org/10.1016/j.watres.2023.120331

| 2.4 |

Pivotal shifts in the water and wastewater sector: new role of ICA guiding data-driven innovation

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Introduction

Digital transformation has emerged as a driving force and a key element in the transition journey for the water sector towards more efficient and sustainable systems. Utilities and industry are under increasing pressure to respond to both long-standing and emerging challenges, including water scarcity and pollution, climate change impacts, population growth and urbanization, ageing infrastructure, and tightening regulatory requirements. Within this shift, the role of instrumentation, control and automation (ICA) is evolving towards a more data-centric discipline that connects monitoring technologies, process optimisation and smart decision-making. The exponential growth, accessibility and penetration of digital technologies (e.g. new monitoring technologies, advances in ICT and automation, real-time modelling and data-driven approaches), offer unlimited potential to develop digital solutions and exploit the value of data, and therefore to tackle the mentioned challenges across the entire water cycle.

In this contribution, the ICA Specialist Group put forward different technological trends that are (or will be) shifting gears in this transformation. This overview focuses on ongoing digitalisation efforts, highlighting their value potential and key challenges. By learning from experience replication of successful approaches is facilitated, fostering collaboration and accelerating the digital transformation journey for the water and wastewater sector.

Key terminology

Apart from the traditional technology in the field of ICA, new terms are becoming increasingly popular, especially linked with data-driven approaches, thanks to their potential applications:

- **Agentic AI:** Artificial intelligence (AI) system that can accomplish a specific goal with limited supervision. It consists of AI agents-machine learning models that mimic human decision-making to solve problems in real time. The term "agentic" refers to these models' agency, or their capacity to act independently and purposefully. Agentic AI builds on generative AI techniques by using large language models (LLMs) to function in dynamic environments. While generative models focus on creating content based on learned patterns, agentic AI extends this capability by applying generative outputs toward specific goals.
- **Generative AI**: Also called gen AI, is AI that can create original content such as text, images, video, audio or software code in response to a user's prompt or request. Gen AI relies on advanced deep learning models algorithms that simulate the learning and decision-making processes of the human brain. These models work by identifying and encoding patterns and relationships in huge amounts of data, and then using that information to respond with relevant new content. AI has been a hot technology topic for the past decade, but generative AI has thrust AI into worldwide headlines and launched an unprecedented surge of AI innovation and adoption.

The use of AI and in particular agentic and gen AI is opening new opportunities for ICA in the water sector. The most noteworthy are AI agents that can interpret and escalate sensor anomalies, suggest process improvements, draft regulatory reports, generate training documentation and training materials; these are all based on the continuous stream of operational data. Just like data requires context for it to be of any use, AI agents require standardised interfaces and tools to interact with external systems.

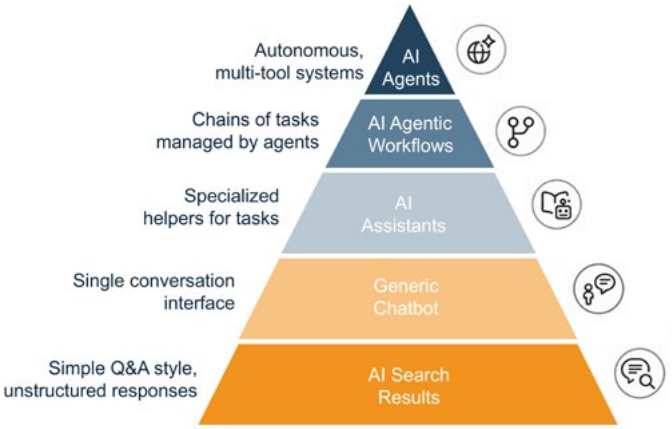


Figure 2.12. The evolution of AI: from static search to autonomous agents. Source: Adapted from Mounce et al., 2025.

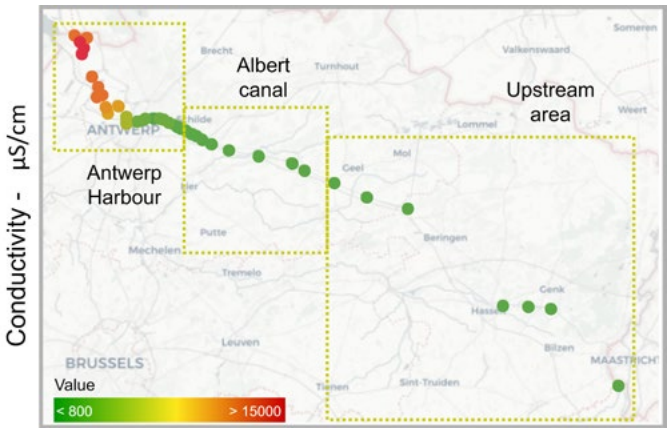


Figure 2.13. IoT real-time monitoring network (water quality and water quantity) around the Antwerp area (> 120 km). Source: Alferes et al., 2024.

- **IoT sensors/networks:** The Internet of Things (IoT) refers to interconnected systems of smart devices with embedded sensors collecting and exchanging real-time physical data (e.g. temperature, water quality, light), using wireless communication protocols like wi-fi, Bluetooth, or LoRaWAN, transforming raw data into actionable insights for broad applications. Components include sensors, end devices and gateways. IoT can, and in many ways already is, revolutionising how environmental data is tracked and analysed, offering insights for example into the patterns and effects of climate change.

- **IT/OT convergence:** integration of information technology (IT - data, software, business systems) with operational technology (OT - physical machines, industrial control, sensors) to create a unified data-driven environment for smart factories and to optimise industrial operations. This convergence marks a crucial shift in water and wastewater operations. In the past, both domains operated primarily in isolation within proprietary architectures resulting in siloed systems, incompatible data models, and costly custom integrations that hindered true operational agility. By embracing integrated IT/OT frameworks, organisations have started paving the way for real-time insights, more streamlined operations, and more connected infrastructure.

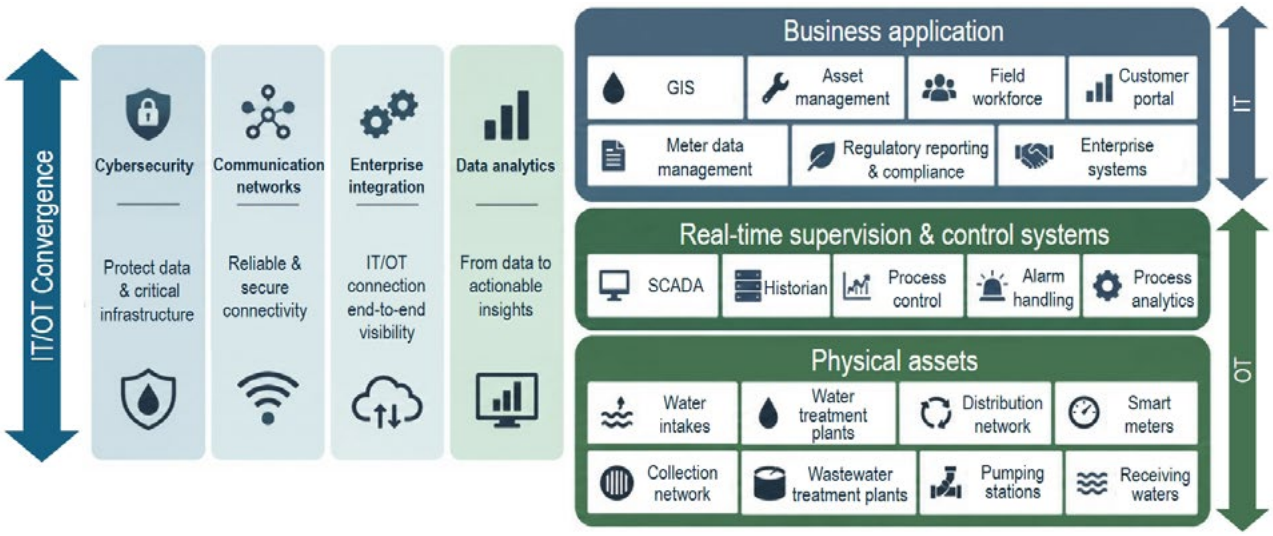


Figure 2.14. Example model of IT/OT convergence in the water industry. Source: Adapted from Infotech 2024.

- **Metadata:** Data describing or providing information about the data. Although metadata isn't a new concept, its importance has become more and more evident in any digital and data transformation. The immense volume of data generated by digital systems has highlighted an interpretation bottleneck: while accessing information is getting easier than ever, understanding its context and meaning is often more difficult. Metadata is then the key to turn large volumes of raw data into representative, reliable, interpretable and useful data both for humans and machines.

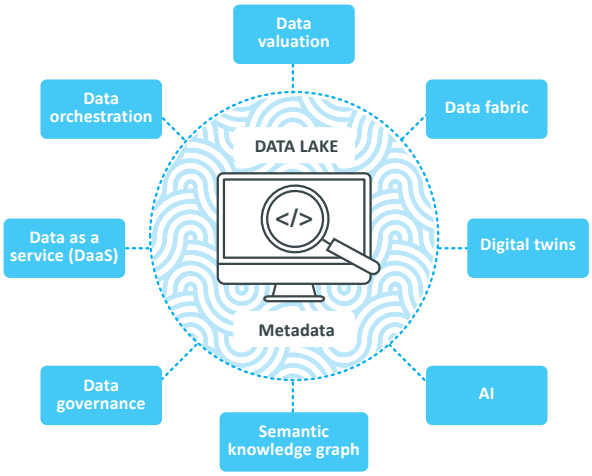


Figure 2.15. Current and future development areas where metadata will play a relevant role. Source: Villez et al., 2024.

Key insights and case studies

Case study 1: Yorkshire Water: Agentic AI for wastewater network risk and wet-weather operational planning

Wastewater network operations during forecast heavy rainfall are highly time-critical, requiring utilities to anticipate storm and emergency overflow activations and mitigate pollution risk through preventive and reactive interventions. To address this, Yorkshire Water's team partnered with the operational control centre to develop an AI powered decision-support solution focused on wastewater assets and environmental impact prevention (UKWP, 2025). The pilot wet-weather planning system uses a combination of machine learning, statistical, and generative AI models to predict which assets are likely to be at risk during localised rainfall events, then contextualises those predictions with real-time situational data such as asset availability and network capacity. This produces a prioritised set of recommended operational actions such as mobilising resources or executing preventative or reactive maintenance, actions that are subsequently validated and triaged by control centre staff before execution. The overall design follows a clear agentic pattern: predict, contextualise with constraints, recommend actions, apply human validation, and then act.

Developing the system required overcoming several challenges, including the need to augment traditionally manual and subjective decision-making with real-time intelligence, and the complexity of aligning AI outputs with existing operational processes and imperfect data landscapes. Building trust and adoption was also critical, necessitating strong stakeholder engagement, testing, and validation. Yorkshire Water adopted an iterative pilot approach and rigorously back-tested the solution against historical storm and high-rainfall events, comparing AI-generated recommendations with observed outcomes and established intervention practices to demonstrate value and refine performance.

Case study 2: Veolia + Mistral AI: Generative AI "plant copilot" for wastewater treatment operations

Large multi-site wastewater operators such as Veolia manage thousands of treatment plants and face persistent operational challenges, including fragmented knowledge spread across SOPs, manuals, and incident records; monitoring overload from numerous dashboards, alarms, and data streams and the need to consistently enable and train a geographically distributed workforce. These issues make it difficult to standardise operations, support decision-making, and ensure efficient responses across plants operating at very different scales and conditions.

To address this, Veolia announced a strategic partnership with Mistral AI in February 2025 to integrate a large language model with Veolia's internal data and knowledge base, enabling staff to effectively "have a conversation with the plant". The solution is designed to provide simplified, conversational access to technical knowledge and critical operational data, deliver real-time recommendations and proactive problem-solving, and improve operational efficiency through optimised monitoring and strengthened predictive maintenance (Veolia, 2025). With Veolia managing over 3,200 wastewater treatment plants globally, the initiative is positioned as a scalable GenAI-based operational support layer with broad impact across the organisation.

Case study 3: ChatGPT-integrated platform for anomaly awareness and compliance reporting and automation

Klir positions its platform explicitly for wastewater operations, with a focus on sampling management, National Pollutant Discharge Elimination System (NPDES) permit compliance, and Discharge Monitoring Reports (DMR), including operational alerting when anomalies occur. Klir has also announced the integration of GPT-4 via Microsoft Azure, framing this as a secure way to combine conversational AI with a utility's compliance, sampling, and water-quality datasets. On the operational side, the platform emphasises instant anomaly alerts that notify the right personnel when something is off, supporting timely interpretation and escalation of compliance risks. From an AI perspective, this approach maps to a lightweight agentic workflow rather than full autonomy: detect anomalies, notify responsible roles, and guide the next steps through explanations, task assignment, and reporting. Generative AI is used for natural-language querying, synthesis, and explanation over structured compliance and monitoring data, while keeping outputs grounded in permits, limits, and monitoring plans to avoid fabricated interpretations.

Key challenges include harmonising heterogeneous sampling and laboratory workflows and ensuring the GenAI layer remains constrained to verified data. Wastewater compliance is a strong entry point for GenAI adoption, as DMRs and compliance narratives are high-volume, repeatable, and auditable and so are well suited to AI-assisted drafting and summarisation with human review while pairing anomaly alerts with GenAI explanations provides a practical, low-risk on-ramp to agentic systems.

Case study 4: HRSD - Hampton Roads Sanitation District (Virginia) - GenAI for treatment optimisation

Hampton Roads Sanitation District (HRSD) has emerged as an early adopter of agentic GenAI in wastewater treatment operations, piloting a GenAI-driven "co-pilot" platform in 2025 at one of its 14 treatment plants. The system ingests historical and real-time data from sensors and supervisory control and data acquisition (SCADA) systems to support operator decision-making around energy use and chemical dosing, such as optimising when to run aeration blowers or pumps (Bluefield, 2025). By forecasting influent flows particularly ahead of storm events and simulating operational scenarios, the AI helps operators balance treatment processes in real time to maintain stable performance while improving energy efficiency. The platform was developed collaboratively with DC Water, Clean Water Services, and Metro Water Recovery, with the explicit goal of creating a flexible AI assistant adaptable to different plant configurations.

Early results indicate tangible operational benefits. By leveraging historical process data, the GenAI system has enabled optimisation of chemical and aeration usage, leading to early reductions in O&M costs and more accurate budget forecasting. While initial efforts have focused on incremental cost savings, HRSD's longer-term vision includes automating routine tasks and scaling the platform across all plants. The case underscores that agentic GenAI can augment human expertise, improving efficiency and compliance without replacing staff provided there is sufficient investment in digital infrastructure and workforce training to build trust in AI-supported operations.

Case study 5: GreenTech (China) - "WateRobot" AI agent for autonomous water treatment

GreenTech's WateRobot represents an advanced example of agentic AI in water treatment, functioning as a comprehensive operational "brain" for a treatment plant. The system combines GreenTech's process optimisation and forecasting models with multi-modal AI inputs including computer vision cameras, audio sensors, and infrared monitoring and integrates large language models for decision-making and operator interaction. Designed to operate a treatment facility with minimal human intervention, WateRobot can perceive plant conditions, adjust controls such as pumps, valves, and chemical dosing in real time, and even conduct troubleshooting dialogues through an LLM interface.

In a pilot "new water" facility, the agent managed routine operations and responded to process upsets while consistently maintaining compliance with regulatory discharge limits. Initial deployments showed approximately 50% lower life-cycle costs compared to conventional plants, driven by automation and optimised control strategies. These results point toward the feasibility of unmanned or "lights-out" treatment facilities, sometimes described as achieving "Water Freedom," although regulatory frameworks will need to evolve to certify fully autonomous operation.

Case study 6: WaterLink (Belgium) – IoT sensor network for water quality monitoring in surface water

A real-time smart monitoring and management information system has been deployed in the Antwerp area as part of the AquaSPICE European project, in order to manage water allocation decisions and assess scenarios for long term water and salt balances in view of climate adaptation strategies (Alferes et al., 2024). An IoT real-time monitoring network (with 45 CTD sensors measuring conductivity (C) as a proxy for salinity, temperature (T) and depth (D)) have been deployed along the research area (more than 120 km). LoRaWAN is used for transmission of the high frequency sensor data to a cloud platform. Customised dashboards and data analysis

are also implemented to facilitate a real-time follow-up of the water system and its dynamics. The network is currently being used as an innovative and daily operational tool to support the drinking water company and stakeholders in the area to follow-up salinity dynamics and water availability, both under normal operation conditions and during climate-change related events.

The deployment and operation of monitoring network (encompassing compact, cost-effective and low-power sensors), together with customised dashboards have made possible the availability of continuous water quality information and the analysis of operational scenarios, all supporting an optimised management of the available surface water.

Case study 7: Anglian Water (UK) - OT telemetry unified into an enterprise "Unified Namespace" with Industrial DataOps

Anglian Water set out to dissolve long-standing OT data silos (telemetry/SCADA, third-party vendor feeds, and separate cloud platforms) by building a centralised architecture that could serve multiple IT consumers (analytics, maintenance, reporting) without bespoke integrations. In the published case study (Novotek, 2025), Anglian's objectives explicitly included creating a Unified Namespace (UNS) with an Message Queuing Telemetry Transport (MQTT) broker backbone and introducing an Industrial DataOps layer to standardise and model OT data in real time before it was shared broadly.

HighByte Intelligence Hub (with Novotek's OT DataOps support) is implemented to restructure and contextualise OT data and then publish it into the UNS turning raw tags into governed, reusable "data products." The case highlights typical IT/OT convergence constraints: heterogeneous vendor systems, different data models, and the need to prepare OT data for downstream IT systems while keeping OT reliability intact.

Case study 8: The use of smart water meters and meter data management (SWM) in South Africa

Smart water meters and meter data management (SWM) are being used in South Africa for drought response (for instance during the Day Zero period), demand-side management, water-user behaviour, household water usage, to identify water losses due to leaks and frauds. In this regard, the WaterWise online application (Warren, 2021) aims to promote water conservation. The application works with the smart water meters networks and sends regular data on water consumption, monthly water bills and reminders for payment at the household level.

Analytical tools are also being used in the city of Durban (Makwarela, 2022) for meter data management, enhancing current distribution networks into smart networks (smart grids), reducing the OPEX cost associated with the installation of additional sensors. E-billing services supported by the Standard Bank in partnership with South African municipalities are also allowing customers to follow up their water and sanitation bills through different online applications (e.g. MyBill and EasyPay). SMS notifications were also effective during the lockdowns caused by the covid-19 pandemic (Mantogo, 2020). Switching to e-services was the coping mechanism to many South African cities including Johannesburg.

Case study 9: Thames Water (UK) – Standardising "site SCADA" across 50 sites using a modular, templated approach

Thames Water ran a program to replace disparate legacy site SCADA systems across 50 sites using AVEVA System Platform with a standardised/templated (modular) approach (Aveva, 2024). The emphasis was not only technology refresh, but also harmonising implementation patterns so that data structures, visualisation, and operations were consistent across the SCADA estate one of the most practical forms of IT/OT "merger" because it reduces site-by-site uniqueness that blocks enterprise integration.

This template-driven standardisation was coupled with updates to Thames Water's internal SCADA standards and adoption during delivery, aiming to produce repeatable deployments that scale across different plant sizes and complexities. In convergence terms, this is the "OT foundation": once the OT layer is standardised, IT capabilities (central historians, analytics, asset performance, reporting) can be integrated far more reliably and cheaply than when each site is a bespoke build.

Case 10: Immokalee Water & Sewer District (Florida, USA): Centralising SCADA + smart meter + weather into one operational platform

Immokalee Water & Sewer District implemented a convergence pattern common to smaller utilities: unify disparate OT/edge sources into one IT-grade operational view. In Xylem's case study, the district centralised and integrated data from smart meters, SCADA systems, and weather sources into the Xylem Vue platform to support faster operational response, pressure/quality tracking, and early leak detection. This clear IT/OT integration combined control and monitoring data (SCADA), field and AMI telemetry, and external contextual data (weather), into a unified environment that operations staff can use in real time. It demonstrates how convergence is often driven by resilience needs (rapid response, event readiness) and by reducing swivel-chair operations across multiple systems one of the quickest routes to measurable value.

Conclusions and recommendations

The reviewed case studies across the water sector illustrate that emerging digital technologies are enabling transformation of instrumentation, control and automation (ICA) and are being applied to improve water and wastewater operations. Gen AI and Agentic AI are being used for process optimisation, failure prediction, and to automate reporting and knowledge capture. The latest developments shift from generative AI as "writing assistance" toward more credible support for complex engineering and operational problem solving, while creating a clearer path to more practical utility-scale deployment.

Across early adopters, reported benefits include improved compliance performance, faster root-cause analysis, and significant savings in staff time and operational resources. At the same time, utilities consistently emphasise that added value strongly depends on execution fundamentals: fit-for-purpose data, workforce engagement, management adaptation, cybersecurity, and clear governance. In practice, the highest added value occurs when advanced data-driven solutions are tightly coupled with domain expertise, robust operational procedures, and an explicit human-in-the-loop validation model.

Several lessons recur across deployments. First, operational constraints—such as treatment capacity, process stability windows, maintenance schedules, and asset availability—must be embedded in optimisation and decision-support logics. Second, systematic back-testing and performance monitoring are essential to establish credibility, manage drift, and move beyond the "AI hype". Third, transparency and traceability (what the system recommended, why, and what data it relied on) are non-negotiable for operational adoption and regulatory confidence.

On the other hand, the historical separation of IT and OT is slowly dissolving as utilities and industry face growing pressure to optimise processes to reduce energy consumption while meeting increasingly stringent regulatory requirements. By embracing integrated IT/OT frameworks, organisations have started paving the way for real-time insights, more streamlined operations, and more connected infrastructure. Integrating traditional IT tooling and concepts (e.g. data analytics, cloud computing, CI/CD DevOps, containerisation) with OT systems (e.g. process historians, process automation logic) has given operational stakeholders the possibility to easily access data from online sensors, lab information systems, controllers, third party IoT devices, and external applications in a unified framework. This improvement of data accessibility through industrial data platforms will undoubtedly accelerate the speed at which fact-based operational decisions are made within organisations of the future.

With the opportunities also come the challenges. Currently, standard best practices for data collection, data storage and data management are lacking, with mostly silo systems, making data exchange and interoperability particularly difficult. This also leads to 'data graveyards' and the lack of 'good' and useful data to be properly used within data driven solutions, real-time control, process optimisation and decision making. Careful data management practices at utilities should prioritise data readiness: standardised data collection, critical metadata (where/when/how/why data was generated), quality assessment, and lifecycle management. A useful starting point is the recent IWA Scientific and Technical Report *Metadata Collection and Organization in Wastewater Treatment and Wastewater Resource Recovery Systems* (Villez et al., 2024), which provides practical guidance on metadata concepts, implementation, and data quality assessment for wastewater applications.

Embracing digitalisation and the new role of ICA within this transformation journey will pave the way for resilient, efficient and sustainable water systems, improving operations and a proper management of the water resources.

References

Acn newswire. 2025. Press release: GreenTech Launches "WateRobot AI Agent" Pioneering a New Path for Industrial Water Savings and Efficiency with AI. https://www.acnnewswire.com/press-release/english/102695/greentech-launches-'waterobot-ai-agent'-pioneering-a-new-path-for-industrial-water-savings-and-efficiency-with-ai#:~:text=Wang%20Xiaoyu%2C%20General%20Manager%20of,applied%20in%20newater%20house%20water. Accessed December 2025

Alferes J., Desmet N., Kempeneers S., Latte S. Hitsov I., Jayaweera C., De Neve K., Wauman J., Bosch R., Dehaspe J., Van Ermen S., Seuntjens P. Genne I. 2025. Water-smart strategies to support decision-making for water resource management in the industrial context. *Water Sci Technol*, 90 (8): 2276–2290. doi: https://doi.org/10.2166/wst.2024.326

Aveva. 2024. Thames Water: Moving to a Standardized Modular Approach for their Site SCADA Applications with AVEVA System Platform. https://www.aveva.com/en/perspectives/presentations/2024/thames-water--moving-to-a-standardized-modular-approach-for-their-site-scada-applications-with-aveva-system-platform/. Accessed December 2025.

Bluefield. 2025. White paper: Reimagining Water Management: Generative AI as a Strategic Utility Asset. https://swan-forum.com/wp-content/uploads/2025/10/Reimagining-Water-Management-Generative-AI-as-a-Strategic-Utility-Asset Report.pdf#:~:text=and%20chemical%20dosing,to%20the%20development%20of%20a. Accessed December 2025

Infotech. 2024. Drive a Fit-for-Purpose IT/OT Convergence Improvement Plan for Your Utility. https://www.infotech.com/research/ss/drive-a-fit-for-purpose-it-ot-convergence-improvement-plan-for-your-utility. Accessed January 2026.

Makwarela E., Mamanyuha A. 2022. Leveraging Advanced Metering Infrastructure data for operational efficiency. 30th Southern African Universities Power Engineering Conference (SAUPEC), 2022, pp. 1-3, doi: 10.1109/SAUPEC55179.2022.9730681

Mantogo Jolidee. 2020. Press release: City of Johannesburg introduces web link billing (sms notification) for municipal statements during covid-19 lockdown period. https://www.johannesburgwater.co.za/city-of-johannesburg-introduces-web-link-billing-sms-notification-for-municipal-statements-during-covid-19-lockdown-period/ Accessed January 2026.

Mounce S, Mounce R, Boxall J. 2025. AI-Augmented Water Quality Event Response: The Role of Generative Models for Decision Support. *Water*. 2025; 17(22):3260. https://doi.org/10.3390/w17223260.

Novotek. 2025. White paper: Getting data flowing for Anglian Water. https://www.highbyte.com/hubfs/marketing-assets/HighByte-Novotek-Anglian-Water-Case-Study.pdf. Accessed December 2025.

UKWP. 2025. White paper: AI within reach. The UK Water Partnership. https://www.theukwaterpartnership.org/wp-content/uploads/2025/04/Appendix-AI-Whitepaper-1.pdf. Accessed December 2025

Veolia. 2025. Press release: Veolia and Mistral AI_ join forces to revolutionize resource efficiency management with generative AI and accelerate the ecological transformation. https://www.veolia.com/en/our-media/press-releases/veolia-and-mistral-ai-join-forces-revolutionize-resource-efficiency. Accessed December 2025.

Villez K., Aguado D., Alferes J., Plana Q., Ruano M.V., Samuelsson O. 2024. Metadata Collection and Organization in Wastewater Treatment and Wastewater Resource Recovery Systems. https://doi.org/10.2166/9781789061154. IWA Publishing, 2024.

Warren B. 2021. Investigation into a SmartPhone Application for Household Water Data Management as a Tool to Improve Conservation Efforts. Stellenbosch University. http://scholar.sun.ac.za/handle/10019.1/109789. Accessed January 2026.

Xylem. 2025. Press-release: Immokalee Water & Sewer District: deployment of a comprehensive water management solution. https://www.xylem.com/en-us/resources/case-studies/xylem-vue-immokalee-water-sewer-district/. Accessed December 2025.



| 3 |

Water, sanitation, and public health

| 3.1 |

From disinfection to water safety: emerging technologies for integrated sanitation and resilient water systems

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Introduction

Safe water is a human right for which disinfection is an undeniable requirement; nevertheless, currently, its provision is still a serious and complex worldwide challenge due to innumerable associated problems, from unbalanced distribution to lack of economic resources. Recently, the United Nations (UN) indicated in the annual Sustainable Development Goals (SDGs) 2025 report that despite worldwide progress (from 2015 to 2024) on access to drinking water, sanitation, and hygiene services, billions of people still lack services. In addition, water sources are still under significant stress due to contamination, unavailability, and lack of governance, and it is estimated that sustainable water management will not be reached until at least 2049 (UN, 2025). Therefore, significant efforts on this matter are urgently required.

In this regard, the IWA Disinfection Specialist Group's (DSG) mission is to share and provide insights into advances in both the science and practical application of treatments to disinfect water, wastewater, and sludge, which directly impact not only water quality and sanitation but also public health and environmental sustainability. Over the past 13 years of activity, the main goal of the DSG has been focused on highlighting effective, safe, and sustainable water disinfection applications but also simultaneously facing the challenge of unwanted disinfection by-products (DBPs) formation and its associated potential health risks, which are closely aligned with several SDGs (mainly SDG 6, but also SDGs 11, 12, 13 and 17).

Concern about DBP generation associated with disinfection of arises from the fact that DBPs result from reactions between chemical agents used as disinfectants (mainly chlorine, but also ozone and peroxide acids) and naturally (or anthropogenically) occurring organic/inorganic matter in water. DBPs can be ubiquitous in disinfected waters at very low concentrations (ng/L to µg/L) (Richardson and Ternes, 2018). Since chloroform was first detected in disinfected water and its carcinogenicity association was discovered in 1974 and 1976, respectively (Rook, 1974; Page and Saffiotti, 1976), significant research efforts have been made to increase knowledge related to DBPs, including the generation, transformation, degradation routes, toxicity dose-responses, chemical stability, and fate in distribution systems, among many other aspects (Tang et al., 2020; Du et al., 2025). Among DBPs, trihalomethanes (THM) and haloacetic acids (HAA) are the most common, well-known, and regulated compounds. Nevertheless, more than 700 DBPs have been identified to date, a number considered an underestimate, and which is expected to increase as detection analytical equipment and methodologies improve (Du et al., 2025). Therefore, the critical trade-off in drinking water quality management is to have a rigorous disinfection effect, limiting the generation of DBPs to values established in water regulations, as summarised in Table 3.1. Regarding wastewater reclamation and reuse, in Europe, only Italy regulates THMs, with a maximum permitted concentration of 30 µg/L (LID, 2006).

In addition, another current emerging challenge related to water is antimicrobial resistance. This natural microbial phenomenon, commonly characterised by a loss of susceptibility to a certain disinfecting agent (commonly associated with antibiotics), has arisen as a significant problem for human health, characterised by the World Health Organization (WHO) as a top global public health and development threat (WHO, 2023). Currently, there is wider information about the presence and spread of antibiotic-resistant bacteria as well as their associated plasmid-borne antibiotic resistance genes in the environment, where wastewater is recognised as a “hot spot” (Rizzo et al., 2013; Cheng and Hong, 2017; Wang et al., 2020) due to the confluence of antibiotics and bacteria. Nevertheless, there are no standards for monitoring and control of this phenomenon specifically addressed in any of the current water legislations for both drinking water and wastewater reclamation and reuse.

Table 3.1 Comparison of regulated DBPs in different guidelines for drinking water

	USA		Europe	China	Australia
	MCL (mg/L)	MCLG (mg/L)	(mg/L)	(mg/L)	(mg/L)
Total THM	0.080		0.1*	≤ 1**	0.25***
Chloroform		0.07		-	
Bromodichloromethane		Zero		0.06	
Dibromochloromethane		0.06		-	
Bromoform		Zero		0.1	
HAA5	0.060		0.060****		
Monochloroacetic acid		0.07		-	
Dichloroacetic acid		Zero		0.05	0.15
Trichloroacetic acid		0.2		0.1	0.1
Bromoacetic acid		-		-	0.1
Dibromoacetic acid		-		-	
Bromate (using O3)	0.010	Zero	0.010	0.010	0.02
Formaldehyde (using O3)	-	-	-	0.9	0.5
Chlorite (using ClO_2)	1.0	0.8	0.25	0.7	0.8
Chlorate (using ClO_2)	0.7	-	0.25	0.7	-

*MCL: Maximum contaminant level; MCLG: Maximum contaminant level goal (non-enforceable public health goals). *Sum of chloroform, bromoform, dibromochloromethane and bromodichloromethane. **Sum of total of chloroform, chlorodibromomethane, bromodichloromethane, and methyl bromide. ***Sum of trichloromethane (chloroform), bromodichloromethane, dibromochloromethane, tribromomethane (bromoform). ****Sum of monochloro-, dichloro- and trichloro-acetic acid, and mono- and dibromo-acetic acid*

To cover these complex water challenges, the wider DSG specific objectives have been focused on: (1) promoting innovative water (drinking and wastewater), sludge) management disinfection technologies and process integration with conventional (UVC radiation, membranes filtration, chlorine, ozone, and advanced oxidation) technologies, (2) promoting those processes (or integrated processes) that, while maintaining the residual disinfectant effect, allow the control of DBP formation and their precursors, (3) promoting the monitoring, fate, and risk analysis of currently emerging waterborne targets, including DBPs but also the current challenge of the antibiotic-resistant phenomenon, and (4) facilitating technical guidance and capacity-building for practitioners across all resource contexts, from advanced systems in high-income countries to basic safe water management in developing regions.

Key insights

There have been some notable recent advances in innovative processes for water disinfection since the third edition of the IWA Global Trend Report (IWA, 2022), and they are briefly highlighted here:

- **UV-LED:** Compact, energy-efficient alternatives to traditional mercury-based UV lamps offering more flexible deployment and improved environmental footprints. These systems are especially promising for decentralised or small-system applications (Martin-Somer et al., 2023; Oguma, 2023).
- **Organic peroxy acids (peracetic acid (PAA, CH_3CO_3H) and performic acid (PFA, HCO_3H):** They have a wide-spectrum toxicity against pathogens and negligible or non-significant DBPs formation (Dominguez Henao et al., 2018; Ding et al., 2023).
- Electrochemical advanced oxidation processes (EAOPs): Flexible techniques that generate powerful oxidants (e.g. hydroxyl radicals, ozone) in situ, with a broad-spectrum efficiency against pathogen inactivation and recalcitrant

organic compounds, with potentially lower DBPs generation with suitable operating conditions (Pasciucco et al., 2025; Correia et al., 2025).

- Electric field treatment: An electrophysical, chemical-free, disinfection approach (including locally enhanced electric field treatment, LEEFT) that inactivates microorganisms primarily via membrane permeabilisation (i.e. electroporation), has produced multi-log reductions in laboratory studies (and can act synergistically with trace antimicrobial metals), but requires further optimisation for real-world scalability (Wang and Xie, 2023; Kim et al., 2024)

In addition, the application of smart approaches and multi-barrier systems (combining conventional processes and innovative ones) is another key to safer and more resource-efficient water treatment systems, such as:

- Integration of artificial intelligence for smart process control and optimisation, involving machine learning models that utilise routine water quality parameters to predict DBPs, providing early warnings and streamlining routine monitoring (Pascacio et al., 2024; Sikder et al., 2024).
- Integration of best disinfection practices into safe water reuse schemes, involving ozone and ozone-advanced oxidation, membrane technologies coupled with other disinfection processes based on chemicals or light-based disinfection, electric field with conventional chlorination (Jarin et al., 2024; Lu et al., 2023), and nature-based or low-intensity solutions such as constructed wetlands and solar-based technologies (Hernández-Zanoletty et al., 2025).

Furthermore, protecting water sources and reducing DBP precursors are critical for achieving source water protection. Key strategies include:

- Identification of high-risk DBP precursors through integrated toxicity assays and high-resolution mass spectrometry analysis.
- Control of agricultural runoff and limit of industrial pollutant discharges to minimise organic and nutrient inputs to receiving waterbodies.
- Optimisation of treatment processes before disinfection to enhance the removal of hydrophobic and low-molecular-weight organics.

In addition, the monitoring and analysis of antimicrobial resistance and potential emerging pathogens are another key challenge that must be addressed through the investigations into the efficacy of disinfection approaches.

Case studies

Case study 1: The disinfection practice in the water industry during the COVID-19 pandemic: drawing on past lessons to forge a better future

The COVID-19 pandemic brought a large loss of human lives, health, and wealth all over the world. The WHO issued a living guideline for infection prevention and control in the context of coronavirus disease, highlighting disinfection as a key measure among the public health and social measures (WHO, 2020). The comprehensive demands on disinfection during the COVID-19 pandemic should achieve multiple goals: first, to inactivate the pathogen in different environments and surfaces (using the best available disinfection process, Table 3.2); second, to ensure the safety of water, wastewater, air, solid waste and living conditions; third, to avoid the impact on ecology and personal health by disinfectants.

Despite disinfection technologies, good practice is also highly valuable for the global water industry to follow. An example of how good practices may significantly impact controlling and limiting the spread of microbial pathogens was the case of the Wuhan Water Group company, the largest water supplier in the Wuhan metropolitan area (China), which suffered and confronted the COVID-19 pandemic first all over the world. They developed the "Safe Mode", like that in the Windows operating system, to cut off the transmission of the virus as much as possible, with the premise of minimising the internal and external contact of the working staff (Figure 3.1) (Wang and Qiu, 2020). Remarkably, with this system, none of their operators contracted an infection in the water treatment plants during the pandemic, and the water supply remained of high quality (setting Ct value of free chlorine at a minimum of 30 mg/L·min), demonstrating the importance of good practice application as another tool to control the spreading of pathogens and infections.

At the beginning of the COVID-19 pandemic, a letter entitled "Disinfection threatens aquatic ecosystems" was published in the journal *Science*, raising the understandable concern of "Did disinfection or DBPs impact the ecology greatly?" Later, two independent teams investigated the DBP concentration in the tap water, wastewater treatment plant (WWTP) effluent, and lake water in Wuhan once the lockdown of this city was over (Li et al., 2021; Wang et al., 2021). At the operational conditions employed, THMs, HAAs, and nitrosamines concentrations were lower than the standard (SDWQ, 2006), comparable to those in Beijing. Only the risk quotient of HAAs in WWTP effluent was found to be harmful to green algae. Actually, there is no report for the obvious ecological damage in Wuhan, and other heavily disinfected cities in China and other countries.

Table 3.2 The practical disinfection technologies in various scenarios. (Adapted from WHO, 2022)

	Physical disinfection				Chemical disinfection						
Media	**Heating**	**Filtration**	**UV**	**Radiation**	**75% alcohol**	**Cl_2**	**ClO_2**	**O_3**	**H_2O_2**	**PAA**	**I_2, HSO_4.**
Skin					+++	+			++		++
Indoor air	Ventilation	++	+++				+++	+++	+++	+++	
Water	+++	++	+++			+++	+++	+++			++
Wastewater		++	+++			+++	+++	+++		++	
Surface			+++	+++	+++	+++	+++		+++		+++
Instrument	+++										
Clothes	+++		+	+++		+++		++			
Fomite	+++					+++				++	
Vehicle			++			+++	+++	+++			

Note: Those underlined are recommended in the above guidelines. Those in black represent other useful disinfection technologies that can be employed in specific scenarios. +++ means very effective, practical and highly recommended; ++ means effective and applicable; + means slightly effective.

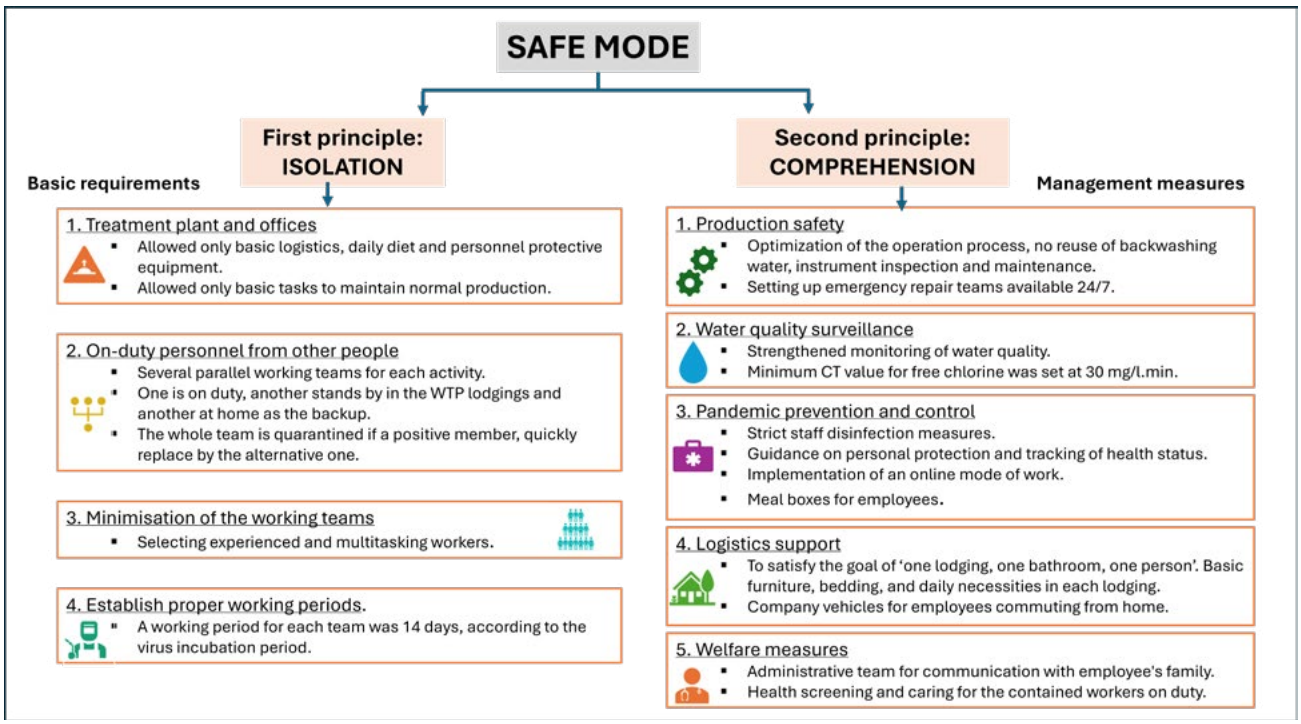


Figure 3.1: General overview of the framework "Safe Mode" applied by the Wuhan Water Group company during the COVID-19 pandemic (Wang and Qiu, 2020)

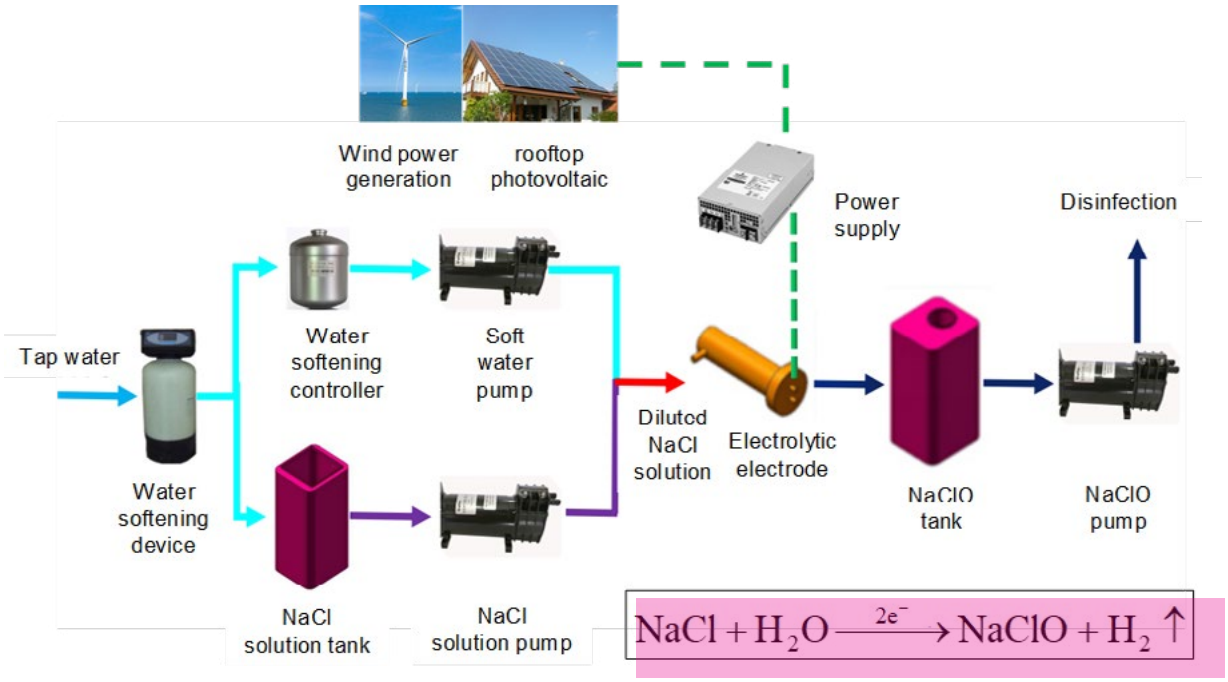


Figure 3.2: Diagram of components of a soda chlorite generator

Case study 2: The onsite soda chlorite (NaClO) generator for small-sized water treatment plants and networks in rural or remote areas

The onsite soda chlorite generator is not new technology, and it is still a very practical solution for water and wastewater disinfection in rural or remote areas all over the world. It can provide the soda chlorite solution of 6,000–8,000 mg/L, which can satisfy the continuous disinfection demand for small-sized water treatment plants and networks (Figure 3.2).

The onsite soda chlorite generator is an environmentally friendly application for disinfection that provides the user with safe operation and large flexibility. It can avoid the large cargo logistics such as the finished product of bleach, oxidants and acid for onsite ClO_2 generation, which is unaffordable for remote areas. It can also avoid the natural degradation of the finished product of bleach and the dangerous storage of oxidants and acid for onsite ClO_2. Moreover, it can provide residual disinfectant effects in networks, while UV or ozone disinfection instruments cannot satisfy this requirement.

According to the wide application records in China (Figure 3.3), the consumption of NaCl to produce soda chlorite is about 4.5 kg NaCl/kg Cl_2, the electricity used is about 5 kWh/kg Cl_2, and the direct disinfection cost is only 5.5 RMB/kilo m^3 water when adding 1 mg/L of disinfectant (as Cl_2), that is about 0.8 $/kilo m^3 water. In addition, the use of clean energy like wind power generation or rooftop photovoltaic, which is quite abundant on islands or inland farms, gains more flexibility in energy restrictions, reduces the energy cost and CO_2 emission.

Case study 3: The use of peroxy acids for disinfection in WWTPs

Over the last 15 years, the use of peroxy acids (mainly PAA and PFA) as alternative disinfectants in water and wastewater disinfection has increased for the following reasons: wide bactericidal and virucidal spectrum at low doses (< 20 mg/L); low or null DBPs generation; innocuous decomposition products (PAA decomposes into H_2O, O_2, and acetic acid; and PFA decomposes into formic acid, H_2O, H_2O_2 and CO_2, all biodegradable and safe for the environment); low dependency on physicochemical water parameters; ease of control, operation and automatisation processes; and competitive cost. In addition, PFA shows a higher microbial efficiency in shorter times, and against viruses and spores, than PAA (Bagagnan et al., 2024). In addition, they have been authorised as biocides in Europe (Regulation (EU) 2025/1260 and the European Chemicals Agency (ECHA) for PAA and PFA, respectively).

Several full-scale applications of PAA and PFA for disinfection have been conducted and implemented in the USA and Europe in the last two decades (Levine et al. 2017; Hilts et al. 2018; Rocher and Azimi, 2021). Among them, it is worth noting that the recent selection of PFA disinfection for the 2024 Olympic Games, held in Paris on the Seine River (Paysant and Yvon, 2024), required several years of study from lab to full scale. The 2018 full-scale trials at the Seine Valenton WWTP (capacity 550,000 m³/day) evaluated PFA disinfection (Figure 3.4). PFA doses ranged from 0.8 to 2.2 mg/L, with C×t values between 15–75 mg/L·min (median: 32 mg/L·min). Results showed average removals of 2–2.5 log for *E. coli* and intestinal

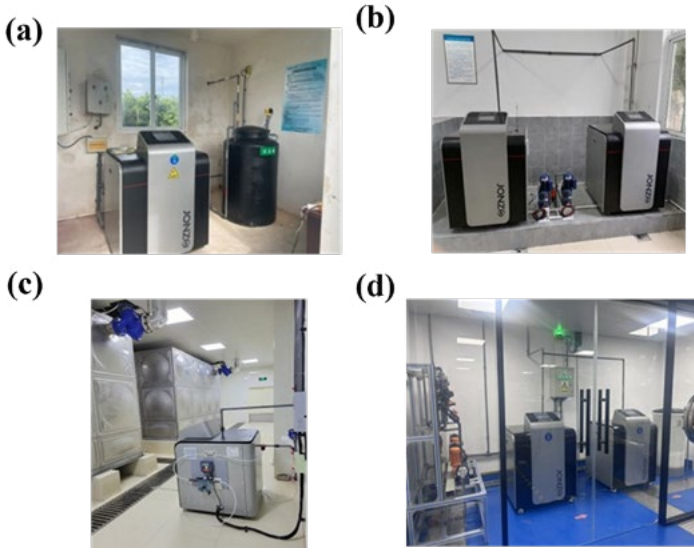


Figure 3.3: Images of onsite soda chlorite (NaClO) generators installed in different locations in China: a) a remote island in Zhoushan, Zhejiang province, b) a rural groundwater supply station in Zitong, Sichuan province, c) a secondary water supply of high building in Jinan, Shandong province, and d) a secondary chlorine addition in a long network in Suzhou, Jiangsu province



Figure 3.4: PFA disinfection implementation at full scale (Seine Valenton WWTP) (Rocher and Azimi, 2021)

enterococci, meeting EU bathing water standards (< 900 and < 330 MPN/100 mL, respectively). Higher C×t values (> 50 mg/L·min) reduced pathogens to below 100 MPN/100 mL. Daily monitoring revealed lower nighttime residuals due to longer hydraulic retention. However, disinfection efficiency decreased during degraded WWTP operations with higher TSS (8.1 vs 4.1 mg/L), especially for enterococci (drop from 2.35 to 1.41 log removal). PFA showed limited effect on sulfite-reducing anaerobes but eliminated F-specific RNA phages in one case. Side effects were minor: slight increases in DOC (+1.2 mg-C/L), COD (+2 mg-O_2/L) and AOX (+10–41%), but no bromate formation. Statistical models confirmed influent quality (TSS, COD) as reliable proxies for optimising PFA dosing. Thanks to the implementation of PFA disinfection, the athletes competed in several river-based events in the Olympic Games in 2024.

Case study 4: Developments in water reuse schemes (including disinfection)

The increasing demand of clean drinking water (or equally clean process water) is obviously challenged by regional water scarcity which is often the consequence of climate change. The focus on reusing treated wastewater in many applications is therefore growing. One big concern is the microbiological safety of the reuse water which requires sound disinfection standards including validation and monitoring.

A global overview on water reuse for drinking water is presented an Australian initiative Water360 which includes a global map of installed systems (https://water360.com.au/map/). The references include the indirect potable reuse (IPR) scheme for Jourdain in France which is an important demonstration project (https://www.vendee-eau.fr/programme-jourdain-vendee-reut-aep/). A multi-barrier approach combining ultrafiltration, low pressure reverse osmosis, UV, and chlorination ensures the production of fresh water that complies with all relevant quality standards.

While Europe has not developed a regulatory framework for direct potable reuse (DPR), the regulation of the minimum requirements for reuse of treated wastewater for irrigation purposes was released in 2020 (Regulation (EU) 2020/741). There are several levels of quality standards requiring different maximum level of contamination with E. coli as indicator. The highest quality standard “A” asks for the validation of certain log inactivations of for example F-specific coliphages and *Clostridium perfringens* spores. An extensive pilot project was conducted in Schweinfurt, Germany with different processes to form a first basis for such a validation approach (Ho et. al, 2024).

Conclusions and recommendations

Although analytical methods for regulated DBPs (such as THMs and HAAs) are well-established, routine monitoring of THMs and HAAs remains a significant challenge in many underdeveloped and economically disadvantaged regions. This pressing issue underscores the urgent need to develop machine learning models that can predict DBP levels based on routine water quality parameters. Furthermore, some areas arbitrarily lower disinfectant doses to comply with DBP limits, neglecting the concurrent risk of microbial contamination. Thus, there is a critical need to develop multi-objective optimisation systems, which adaptively optimise disinfectant dosage in response to changing water quality, effectively balancing microbial inactivation with the control of disinfection by-product formation.

Future efforts should prioritise energy-efficient technologies, improved precursor and DBP monitoring, and integrated process control to ensure safe, sustainable, and scalable disinfection practices.

References

Bagagnan, S., Jusselme, M.D., Alphonse, V. Guerin-Rechdaoui, S., Marconi, A., Rocher, V., Moilleron, R. (2024). Assessing the effectiveness of performic acid disinfection on effluents: focusing on bacterial abundance and diversity. *Environmental Science and Pollution Research* 31, 58252–58262.

Cheng, H., & Hong, P. Y. (2017). Removal of antibiotic-resistant bacteria and antibiotic resistance genes affected by varying degrees of fouling on anaerobic microfiltration membranes. *Environmental Science & Technology* 51(21), 12200-12209.

Correia, S.E., Lacasa, E., Cañizares, P., Rodrigo, M.A., Sáez, C. (2025). Energy-efficient electro-ozonizers: A solution for antibiotic-resistant bacteria (ARB) in wastewater. *Process Safety and Environmental Protection* 201, Part B, 107639.

Ding, N., Li, Z., Jiang, L., Liu, H., Zhang, Y., Sun, Y. (2023). Kinetics and mechanisms of bacteria disinfection by performic acid in wastewater: In comparison with peracetic acid and sodium hypochlorite. *Science of the Total Environment* 878, 162606.

Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption (recast). *Official Journal of the European Union*. OJ L 435, 23.12.2020, pp. 1–62.

Dominguez Henao, L., Turolla, A., Antonelli, M. (2018). Disinfection by-products formation and ecotoxicological effects of effluents treated with peracetic acid: a review. *Chemosphere* 213, 25–40.

Du Z., Fu, M., Zheng, S., Li, X., Chen, J., Li, J. (2025). A time-updated review on the identification of emerging disinfection byproducts in drinking water: Revealing the role of chromatography. *Trends in Environmental Analytical Chemistry* 47, e00267.

ECHA, European Chemicals Agency. Performic acid generated from formic acid and hydrogen peroxide. Article 95(1) of the Biocidal Products Regulation (BPR) https://echa.europa.eu/substance-information/-/substanceinfo/100.242.239 https://echa.europa.eu/documents/10162/5604808/art95_list_en.pdf/f6dae020-1e04-b1fd-699f-f17a3bc2efc4?t=1759141498044 (Accessed October 2025).

Hernández-Zanoletty, A., Oller, I., Polo-López, M.I., Jambrina-Hernández, E., Plaza-Bolaños, P., Agüera, A. (2025). Upgrade constructed wetlands wastewater quality by solar-driven photochemical quaternary treatments in raceway pond reactor at pilot plant scale. *Science of the Total Environment* 958, 178058.

Hilts, B., Morgan, S., Goldman, J., Stewart, S., Garibi, A. (2018). Procuring & delivering the two largest WRRF PAA disinfection systems in the world—Memphis style. *Proceedings of the Water Environment Federation* 17, 456–460.

IWA Global Trends and Challenges Water Science, Research and Management, 3rd Edition, 2022. https://www.iwa-network.org/publications/global-trends-and-challenges-in-water-science-research-and-management (Accessed October 2025)

Jarin, M., Wang T., Xie, X. (2024). Operando investigation of the synergistic effect of electric field treatment and copper for bacteria inactivation. *Nature Communications* 15, 1345.

Ho, J., Ahmadi, J., Schweikart, C., Hübner, U., Schwaller, C., Tiehm, A., & Drewes, J. E. (2024). Assuring reclaimed water quality using a multi-barrier treatment train according to the new EU non-potable water reuse regulation. *Water Research*, 267, 122429.

Kim, Y.-J., Huo, Z.-Y., Wang, X., Dai, H., Lee, D.-M., Suh, In-Y., Hwang, J.-H., Chung, Y., Lee, H. Y., Du, Y., Ding, W., Kim, S.-W. (2024). Walking-induced electrostatic charges enable in situ electroporated disinfection in portable water bottles. *Nature Water* 2, 360–369.

LID. Legislativo Italian Decree 99, 1, n.152, Norme tecniche per il riutilizzo delle acque reflue, ai sensi dell'articolo 99, comma 1, del decreto legislativo 3 aprile 2006, n. 152., April 3

Levine, L., Hennagir, C., MacDougall, J., Steward, S.A., Eaton, A.P. (2017). Peracetic acid disinfection for industrial wastewater treatment—Washburn tunnel case study. *Proceedings of the Water Environment Federation* 13, 1490–1499.

Li, Z.G., Song, G.F., Bi, Y.H., Gao, W., He, A.E., Lu, Y., Wang, Y.W., Jiang, G.B. (2021). Occurrence and distribution of disinfection byproducts in domestic wastewater effluent, tap water, and surface water during the SARS-CoV-2 pandemic in China. *Environmental Science and Technology* 55, 7, 4103-4114.

Lu, Y.-W., Liang, X.-X., Wang, C.-Y., Chen, D., Liu, H. (2023). Synergistic nanowire-assisted electroporation and chlorination for inactivation of chlorine-resistant bacteria in drinking water systems via inducing cell pores for chlorine permeation. *Water Research* 229, 119399.

Martín-Sómer, M., Pablos, C., Adán, C., van Grieken, R., & Marugán, J. (2023). A review on LED technology in water photodisinfection. *Science of the Total Environment*, 885, 163963.

NHMRC, NRMMC (2011) Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra. Version 4.0 Updated June 2025.

Oguma, K. (2023). Field demonstration of UV-LED disinfection at small and decentralized water facilities. *Journal of Water and Health*, 21, 1369–1384.

Page, N.P., Saffiotti, U. (1976). Report on the carcinogenesis. Bioassay of chloroform. U.S. Department of Health, Education, and Welfare. National Cancer Institute. Carcinogenesis Technical Report Series.

Pascacio, P., Vicente, D. J., Salazar, F., Berruti, I., Nahim, S., Polo, M. I., & Oller, I. (2024). Implementation of machine learning models for predicting the inactivation performance of escherichia coli in wastewater through varied photo-chemical processes and aqueous matrix combinations. In *International Conference on Wider-Uptake of Water Resource Recovery from Wastewater Treatment* (pp. 388–393). Cham: Springer Nature Switzerland.

Pasciucco, R., Pasciucco, F., Iannelli, R., Pecorini, I. (2025). Potential applications of electrochemical advanced oxidation processes (EAOPs) as tertiary and quaternary wastewater treatments under the new Directive EU 2024/3019: A review. *Journal of Water Process Engineering* 77, 108494.

Paysant, D., Yvon, P. (2024). Paris dreams of swimming in the Seine part of its Olymics visión. https://phys.org/news/2024-07-paris-seine-olympics-vision.html?utm_source=chatgpt.com (Accessed October 2025).

Regulation (EU) 2025/1260 of 26 June 2025. *Official Journal of the European Union*. OJ L, 2025/1260, 27.6.2025. http://data.europa.eu/eli/reg_impl/2025/1260/oj

Richardson, S.D., Ternes, T.A. (2018). Water analysis: emerging contaminants and current issues. *Analytical Chemistry* 90, 398-428.

Rizzo, L., Manaia, C., Merlin, C., Schwartz, T., Dagot, C., Ploy, M.C., Michael, I., Fatta-Kassinos, D. (2013). Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: a review. *Science of the Total Environment* 447, 345–360.

Rocher, V., Azimi. S. (2021). *Effectiveness of Disinfecting Wastewater Treatment Plant Discharges: Case of Chemical Disinfection using Performic Acid*. IWA Publishing. DOI:10.2166/9781789062106_xx

Rook, J.J. (1974). Formation of haloforms during chlorination of natural waters. *Water Treatment and Examination* 23, 234–243.

Sikder, R., Zhang, H., Gao, P., & Ye, T. (2024). Machine learning framework for predicting cytotoxicity and identifying toxicity drivers of disinfection byproducts. *Journal of Hazardous Materials*, 469, 133989.

SDWQ. Standard for Drinking Water Quality (GB/T5749-2006). China. https://www.dgav.pt/wp-content/uploads/2022/06/China-GB-5749-2006_Standards-for-Drinking-Water-Quality.pdf (Accessed October 2025).

Tang, Y., Long, X., Wu, M., Yang, S., Gao, N., Xu, B., Dutta, S. (2020). Bibliometric review of research trends on disinfection by-products in drinking water during 1975–2018. *Separation and Purification Technology* 241, 116741.

United Nations Department of Economic and Social Affairs (2025). The Sustainable Development Goals Report 2025. New York. https://unstats.un.org/sdgs/report/2025/The-Sustainable-Development-Goals-Report-2025.pdf (Accessed October 2025).

US EPA, NPDWR (National Primary Drinking Water Regulations). Comprehensive Disinfectants and Disinfection Byproducts Rules (Stage 1and Stage 2): Quick Reference Guide. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100C8XW.txt (Accessed October 2025).

Wang, J., Chu, L., Wojnárovits, L., Takács, E. (2020). Occurrence and fate of antibiotics, antibiotic resistant genes (ARGs) and antibiotic-resistant bacteria (ARB) in municipal wastewater treatment plant: An overview. *Science of the Total Environment* 744, 140997.

Wang, L.Y., Zhang, X., Chen, S.S., Meng, F.B., Zhang, D.Y., Liu, Y., Li, M., Liu, X., Huang, X., Qu, J.H. (2021). Spatial variation of dissolved organic nitrogen in Wuhan surface waters: Correlation with the occurrence of disinfection byproducts during the COVID-19 pandemic. *Water Research* 198, 117138.

Wang, T., Xie, X. (2023). Nanosecond bacteria inactivation realized by locally enhanced electric field treatment. *Nature Water* 1, 104–112.

Wang, Y.F., Qiu, W.X. (2020). Wuhan Water's 'Safe Mode' during the COVID-19 pandemic. *The Source Magazine* 10, 49–51. https://thesourcemagazine.org/wuhan-waters-safe-mode-during-the-covid-19-pandemic/ (Accessed October 2025).

World Health Organization (WHO) (2020). Cleaning and disinfection of environmental surfaces in the context of COVID-19. https://www.who.int/publications/i/item/cleaning-and-disinfection-of-environmental-surfaces-inthe-context-of-COVID-19 (Accessed October 2025).

World Health Organization (WHO). (2023). https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance. (Accessed October 2025).

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Biofilms: innovative technologies

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Introduction

Biofilms are complex biological structures that form on almost all moist or submerged surfaces (Flemming et al., 2016). They are common in natural and engineered water systems, and can play both beneficial and detrimental roles. Beneficial biofilms include those harnessed for contaminant removal, such as biological filters for drinking water treatment, moving bed biofilm reactors (MBBRs) for wastewater treatment, and riverbank filtration for groundwater treatment. Detrimental biofilms include biofouling layers on reverse osmosis membranes, biofilms in water distribution pipes, and algal mats in lakes.

Innovations in biofilm technology can be divided into four major areas: biofilm microbiology, biofilm reactor technology, control of detrimental biofilms, and biofilm modelling. Each area is discussed in more detail, below.

Key terminology

- **Biofilms:** biological structures consisting of microbial cells and an extracellular polymeric matrix
- **EPS:** extracellular polymeric matrix that binds cells to each other and typically to a surface
- **Biofilm reactor:** a vessel or compartment with biofilms that degrade contaminants
- **Microbial ecology:** the study of microbial communities.

State-of-the-art of biofilm technology

Biofilm microbiology

Biofilms consist of bacteria, yeasts, fungi, algae, or other microorganisms embedded in a self-produced matrix of extracellular polymeric substances (EPS) (Flemming and Wingender, 2010). A unique feature of biofilms is the presence of substrate gradients, which leads to a stratification of microbial activity (degradation rates) and microbial communities (Flemming et al., 2016). The close proximity of different microbial groups within the biofilm allows for complex ecological associations and interactions. Also, it allows for multiple types of processes, e.g. aerobic, anoxic, and anaerobic, to occur simultaneously.

An important goal in biofilm applications is obtaining a desired structure and function. The structure typically refers to physical configuration of the biofilm, such as the thickness, porosity, roughness, EPS composition, mechanical properties, and density. It may also refer to the spatial distribution of bacteria. The function often refers to the microbial groups or functional guilds within the biofilm, including their biocatalytic activity.

The composition and functions of the biofilm microbiome can be determined using different molecular tools. *In-situ* molecular tools, such as fluorescence in situ hybridisation (FISH), can be combined with microscale chemical sensors to explore the structure and function of biofilms (Schramm, 2003). Quantifying specific microbial targets can be realised with quantitative polymerase chain reaction (qPCR). More recently, digital PCR (dPCR), mostly as droplet digital PCR (ddPCR), has become popular (Hindson et al., 2013). Next generation sequencing (NGS) (high throughput sequencing) methods are also increasingly used in biofilm research. Sequencing of

16S rRNA gene amplicons, also referred to as metabarcoding, enables the study of the entire microbial community, or "microbiome," of biofilms. DNA amplicons created by PCR are sequenced on an NGS platform, providing detailed community compositions as well as relative abundances (McIlroy et al., 2015; Santillan et al., 2019). With curated public databases like Silva (Quast et al., 2013), 16S rRNA gene sequences can be classified. The activated sludge-specific database MiDAS (http://www.midasfieldguide.org) (McIlroy et al., 2015) can be more useful for wastewater biofilms.

Increasingly, researchers are employing "shotgun sequencing" to comprehensively sample all genes in all organisms in a given complex sample, i.e. the metacommunity. This provides a more complete view of the functional gene structure of the microbial community (Santillan et al., 2019). It also provides greater taxonomy resolution, functional profiling, and cross-domain (Bacteria, Archaea, and Eukarya) coverage than 16S rRNA gene amplicon sequencing, without the PCR-associated biases. However, this approach is more expensive, produces large amounts of data, and requires more bioinformatics analyses, such as reads assembly and binning, metabolic function profiling, and antibiotic resistance gene profiling.

The investigation of freshwater sediments has revealed a microbial consortium that couples anaerobic methane oxidation to denitrification (Raghoebarsing et al., 2006). This process, also known as DAMO, is performed by bacteria of the NC10 phylum and archaea belonging to the ANME-2D lineage, which respectively reduce nitrite and nitrate (Ettwig et al., 2010; Haroon et al., 2013). Owing to their ability to remove nitrogen by utilising methane as a sole carbon source, intensive research on ways to integrate DAMO microorganisms in bioreactors for nitrogen and methane removal is ongoing. Biofilm reactors has proven particularly useful, as they can facilitate the retention of the slow-growing DAMO microorganisms (Xie et al., 2017).

The continued development of knowledge about phototrophic biofilms has allowed their use for nutrient removal from wastewater, heavy metal accumulation and water detoxification, oil degradation, agriculture, aquaculture, and sulfide removal from contaminated waste streams (Kesaano and Sims, 2014; Wang et al., 2017).

Wastewater treatment processes can be a significant source of nitrous oxide (N_2O), a powerful greenhouse gas (GHG). While the microbial basis of N_2O emissions from nitrifying and denitrifying bacteria are fairly well understood, the mechanisms of N_2O emissions from biofilm systems can be quite different due to substrate gradients and microbial stratification (Sabba et al., 2015; Sabba et al., 2018). Further research is needed to better understand and manage N_2O emissions from biofilm processes.

Biofilms are often correlated with opportunistic pathogens in premise plumbing systems (Liu et al., 2016; Wingender and Flemming, 2011). In particular, there is increasing concern about *Legionella* spp. in drinking water systems (Shen et al., 2015). Biofilm formation is thought to be related to water residence time in premise plumbing systems, which may be increasing due to greater use of water-conserving fixtures, lower building occupancy, and, more recently, building shutdowns or low occupancy due to the Coronavirus pandemic (Ley et al., 2020).

The EPS matrix of biofilms are thought to consist primarily of polysaccharides, proteins, and nucleic acids (Karygianni et al., 2020) although recent research suggest that lipids and glycosylated proteins are more important than proteins and polysaccharides (Lin et al., 2018). The EPS provides biofilms with mechanical stability, mediates bacterial adhesion to surfaces, and serves as the three-dimensional polymer network that interconnects and transiently immobilises bacterial cells inside a biofilm (Flemming and Wingender, 2010). EPS helps entrap particulate matter from the bulk liquid, convert non-readily biodegradable substrate into readily biodegradable substrates, agglomerate metals such as selenium (Gonzalez-Gil et al., 2016), and promote the formation of granular sludge. While the constituents of the EPS matrix are generally known, their full characterisation and function remain elusive (Seviour et al., 2019). The kinetics of EPS production, the rate the constituents degrade, their contribution to metabolic kinetics, and biochemical transformation rates owing to a biofilm are poorly understood. Thus, few biofilm models explicitly describe EPS.

An emerging area of research is on the mechanical properties of biofilms that can impact biofilm deformation and detachment. Several review papers have been published on this topic in recent years (Gordon et al., 2017), and new models are being developed to incorporate mechanical properties and include deformation (Li et al., 2020; Tierra et al., 2015).

Many micropollutants, including pharmaceuticals, have been shown to be degrade biologically. In some cases, biofilm processes can outperform the suspended growth process. This may be due to the greater diversity of microbes and redox conditions in biofilm processes (Torresi et al., 2016). The biochemistry and microbiology of micropollutant transformation – in context of biofilms – is under active investigation.

Biofilm reactor technology

Biofilm reactors are the primary means to harness biofilms to treat water, by transforming environmental pollutants, such as carbon (C), nitrogen (N), and phosphorus (P). Several types of biofilm reactors have been utilised for water treatment, such as biological aerated filters (BAFs) and MBBRs. However, most biofilm reactor applications are combined with suspended biomass in what are known as "hybrid" activated sludge (AS) and biofilm processes. For example, integrated fixed-film active sludge (IFAS) processes, membrane biofilm reactors (MBfRs), membrane-aerated biofilm reactors (MABRs), aerobic granular sludge processes, and mobile biofilm reactors are often, or always, hybrid processes. Generally, biofilm reactors

offer a smaller physical footprint than activated sludge processes that are designed to meet the same wastewater treatment objective. Hybrid processes can provide the same degree of intensification with fewer biofilm carriers, and often can achieve lower effluent contaminant levels.

State-of-the-art MBBRs and IFAS processes use free-moving and plastic carriers to support biofilm growth (McQuarrie and Boltz, 2011). More recently, MBBRs are being used for anaerobic treatment. Different carrier designs can promote different biofilm properties, where for example control of biofilm thickness can prevent carrier clogging as well as select for different biological and physical biofet al., 2020 and Piculell et al., 2016).

Enhanced biological P-removal (EBPR) can be achieved with biofilm and hybrid processes (Boltz and Sims, 2025). The Hias® process moves plastic carriers through a plug-flow reactor and retains and moves them to the front of the reactor with an inclined screen (Saltnes et al., 2017). Cella™ (Veolia) is a MBBR that utilises alternating flow direction and intermittent aeration to promote EBPR in a MBBR (Ossiansson, 2025). This process utilises a bio-based carrier.

Granular biomass is typically utilised in upflow anaerobic sludge blanket reactors. Aerobic granules can be formed and maintained in sequencing batch reactors (SBRs) (Beun et al., 2002) and continuously flowing biological wastewater treatment processes (Boltz and Rittmann, 2024). Application of an anaerobic feeding stage is crucial to obtain a stable and scalable aerobic granular sludge technology (de Kreuk et al., 2005). All of these wastewater treatment plants (WWTPs) are designed for biological nutrient removal from municipal wastewaters. The NEREDA™ process is a commercially available aerobic granular sludge system used for biological nutrient removal in screened/degritted wastewater or primary effluent. The first full-scale NEREDA™ process was installed at the Garmerwolde WWTP, Netherlands (Pronk et al., 2015). The largest facility is in Ringsend (Ireland) with a capacity of 600 MLD or 2.4 million PE. This technology only occupies around 30% of the footprint of a traditional nutrient removal process, and saves significant energy due to the absence of most of the mechanical equipment needed in a conventional process. The NEREDA™ process maintains a constant liquid/biomass volume. The filling, settling, and decanting steps occur simultaneously during approximately 30% of the operational period.

Both granular sludge and MBBR provide an effective platform for simultaneous partial nitritation and anaerobic ammonium oxidation (anammox) based processes, especially for the treatment of anaerobic digester effluents. The ANITA™ Mox process (Veolia) and ANAMMOX (Paques) are examples of MBBR and granular based systems to treat sidestream nitrogen-rich effluent. The ANITA™ Mox process is available in both MBBR and IFAS configuration (Veuillet et al., 2014), where the latter is the preferred choice for digester effluents from thermal hydrolysis processes (THP). For the granular sludge process, upflow sludge blanket reactors, as well as reactors where cyclones or sieves are used to selectively retain the granular anammox biomass in the reactor, are used (Lackner et al., 2014). Current research and development focus on the use of cyclones or sieves for retaining granular biomass as well as using MBBR in the mainstream of continuous flow municipal wastewater treatment processes.

Mobile biofilms and aerobic granules are viable and cost-effective when utilised in continuously flowing biological wastewater treatment processes (Daigger et al. 2023). The mobile-organic biofilm, or MOB, (Nuvoda, U.S.A.) process includes mobile biofilms and their retention screens with a bioreactor and liquid and solids separation process, usually a clarifier. The MOB process can be applied to virtually any process configuration and has been demonstrated to be effective for carbon oxidation, combined carbon oxidation, and nitrification, nitrification, and denitrification. Biofilm retention screens may be integrated with bioreactor effluent, but are commonly integrated with waste-solids streams. Lignocellulosic materials, e.g. kenaf, have been utilised as mobile-biofilm carriers. Mobile biofilms have exceptional settling characteristics that are similar to AEROBIC granular sludge (AGS) (Boltz and Sims, 2026). Boltz et al. (2026) describe the mechanics of hybrid processes in the context of biological nutrient removal (BNR) by simulated AS and MOB processes. The specific surface area of mobile biofilms depends on biofilm thickness; therefore, spherical and spheroidal geometries have been explicitly simulated to describe the MOB process (Boltz and Daigger, 2022; Boltz et al., 2026). It can be operated as a biofilm reactor or hybrid biofilm and suspended biomass process. Full-scale installations exist in the USA, United Kingdom, and Canada. The inDENSE (World Water Works, USA) process utilises hydrocyclones to retain aerobic granules in a wastewater treatment process.

An interesting development is the recovery and use of the EPS matrix of the wasted granular sludge as a gel-forming biopolymer. Such polymers cannot be derived from oil-based chemistry, only from biological resources. This makes the product a potential economic attractive resource that can be produced from wastewater. The current state of the technology is a demonstration facility in the Netherlands operated by the Dutch water boards. It can produce 500 tons of polymer per year, and the polymer is marketed under the tradename Kaumera.

A biofilm reactor that is emerging rapidly is the membrane biofilm reactor (MBfR), or membrane-aerated biofilm reactor (MABR) when used to supply O_2. In these systems, a gaseous substrate is delivered directly to the base of the biofilm via diffusion through a gas-permeable membrane (tubular, hollow-fibre, or flat) on which a biofilm grows. The gaseous substrate can be the electron donor or acceptor. Typically, the electron donor and electron acceptor are subject to counter-diffusion (Nerenberg, 2016; Rittmann, 2018). The most common electron donor is hydrogen gas (H_2) (Rittmann 2018), although methane gas (CH_4) also has been studied (Lv et al., 2018). H_2-based MBfRs have been demonstrated for

reduction/removal of nitrate, nitrite, perchlorate, bromate, selenate/selenite, arsenate, and chromate (Zhou et al., 2019). The common electron acceptor is oxygen gas (O_2), i.e. the O_2-based MBfR or MABR (Martin and Nerenberg, 2012; Syron and Casey, 2008). As the MBfR allows for precise control of the delivery capacity of the gaseous donor or acceptor, biofilms with defined redox conditions can be developed for simultaneous oxic/anoxic process. For example, the MABR may be used for nitritation/anammox and biodegradation of aromatics by a combination of aerobic monooxygenation and anoxic respiration (Pellicer-Nacher et al., 2010). Likewise, the O_2-based MBfR is ideal for bubble-free oxidation of surfactants (Luo et al., 2021; Zheng et al., 2023; Zheng et al., 2025). The H_2-based MBfR is available from APTwater (Pittsburg, California, USA) and JSREET (Suzhou, Jiangsu, China) and is commonly used for removals of nitrate and perchlorate. MABR technology is established for wastewater treatment with commercially available products including Veolia's ZeeLung™ and Dupont's OxyMem™. These O_2-based processes are well suited for combined carbon oxidation and nitrification, nitrification, partial nitritation, and deammonification. They are applied for the intensification of wastewater treatment, while also reducing energy consumption with bubble-less oxygen delivery and mitigating N_2O production. The technology is applied for large-scale municipal projects (e.g.; 151 MLD Bolton wastewater treatment works in the UK) and small, decentralised wastewater treatment applications.

New water-quality regulations and new processes have made established biofilm reactor types relevant to new contaminants. For example, in the USA there are new regulations for steam-power generation facilities that require total-dissolved selenium concentrations to be less than 0.029 mg/L. The biological transformation of selenate to selenite, and selenite to elemental selenium is a cost-effective treatment approach, and anaerobic biofilm reactors are employed (Boltz and Rittmann, 2021). The most widely used processes for selenate removal are Suez's ABMet® and Frontier's SeHAWK®, but other platforms are viable. Both are fixed-bed biofilm systems that promote heterotrophic reductions by the addition of organic donor substrates. H_2 also can be used as an inorganic donor in the MBfR (Zhou et al., 2019)

Biofilms play a special role due to their capacity to generate electrical current in microbial electrochemical cells (Rittmann, 2018). The foundation for microbial electrochemistry comes from bacteria that oxidise simple organic molecules and respire those electrons to the anode of an electrochemical cell. These bacteria have been called anode-respiring bacteria (ARB) and exoelectricigens, and their key attribute is extracellular electron transport of electrons to an anode, generatimg energy for the bacteria (Rittmann and McCarty, 2020; Rittmann, 2018). Once the electrons reach the anode, they are conducted through an electrical circuit to the cathode, where they are used to generate value either as electrical power by reducing O_2 to H_2O, hydrogen peroxide (H_2O_2) through partial reduction of O_2, H_2 gas by reduction of H_2O, or organic molecules by reduction of inorganic carbon (Rittmann, 2018; Rittmann and McCarty, 2020). Microbial electrochemical cells are still at the research and development stage, although some commercialisation efforts are ongoing.

Biofilm processes can be used to capture and valorise CO_2 in biogas and combustion off-gases, and for atmospheric CO_2 capture. The MBfR is especially useful in this context, as it can deliver CO_2 at a high carbon-transfer efficiency (Lai et al., 2022). Another valorisation application is to recover valuable metals, such as palladium and gold by reducing them to nanoparticles that are retained in the biofilm (Zhou et al., 2026; Long et al., 2025). The biogenic palladium nanoparticles are especially good catalyst for a range of reductions (Long et al., 2024).

Control of detrimental biofilms

The deleterious role of biofilms on membranes is also an area of practical concern. Membrane biofouling is a costly operational concern that is a feed spacer problem in spiral wound membranes (Vrouwenvelder et al., 2006). Other unwanted biofilms are in drinking water distribution and sewers. Another approach to dealing with undesired biofilms that grow on membranes is to tolerate their existence, and focus on increasing hydraulic conductivity of the growing biofilms rather than trying to prevent their formation. The biological activity in the biofilm fouling layer may actually improve permeate quality (Chomiak et al., 2015).

Biofilm modelling

Given the complexity of biofilms, modelling is a useful tool that may be used to understand and systematically evaluate them and predict system responses to their incorporation. For example, modelling may be used to optimise a process for performance and cost effectiveness, predict existing system response to a range of simulated operating conditions, and troubleshoot undesirable performance. Biofilm models are commonly used for research and the design and evaluation of bioreactors (Morgenroth et al., 2000). A consensus description and comparison of biofilm models was presented by Morgenroth et al., (2000). Rittmann et al. (2018) presented a framework for good biofilm reactor modelling in practice. One-dimensional biofilm models are widely used in engineering practice (Boltz et al., 2010). Even further simplification can be obtained with 0-D models, neglecting spatial variations and lumping the reaction-diffusion process into apparent half-saturation coefficients for Monod kinetics, (Baeten et al., 2018). Nevertheless, multi-dimensional biofilm models have enhanced many areas of biofilm research and technology development (Martin et al., 2013). A dichotomy exists between the use of biofilm models: one-dimensional biofilm models are typically used for engineering practice and biofilm-reactor research and development, while the more computationally demanding multi-dimensional biofilm models are more commonly used in research.

Numerical, one-dimensional biofilm models are encoded into a majority of commercially available wastewater treatment plant simulators. The methodology for modelling diffusion and reaction of soluble state-variables is similar, but the methods of simulating particulate state-variable movement and biofilm detachment vary significantly among models. In addition, model users generally lack flexibility to easily define and modify the function that describes biofilm detachment.

The importance of bulk-liquid hydrodynamics and system idiosyncrasies (e.g. biofilm carrier type and transport) are an integral consideration for biofilm and biofilm reactor modelers. Biofilm models have been used to address topics most relevant to environmental biotechnology, including hybrid systems, membrane biofilm reactors, aerobic granular sludge, GHG emissions, phototrophic biofilms, and microbial fuel cells.

In addition to bioreactor advancements, strategies for the eradication of deleterious biofilms have resulted from biofilm use. For example, biofilms persistently foul membrane filters. As biofilms grow on membrane surfaces, they increase hydraulic resistance and either decrease filtration fluxes or increase energy costs for a given flux. Many advances in the current understanding of biofilm-associated membrane fouling resulted from the modelling of reverse osmosis systems.

An important question is how to model fluid flow through biofilms. Several recent studies considered the biofilm as a porous media, with Darcy-type behavior. However, studies also have shown that the biofilm can compact during filtration, indicating a reduction in porosity with higher pressure gradients and flows (Jafari et al., 2018). Also models combining adsorption processes and biofilm growth in granular activated carbon filters have made some progress in recent years (Kaiser et al. 2023, 2025)

Overall, biofilm model features can be described with different degrees of complexity. They concern, for example, biological and physicochemical transformations, liquid-phase transport (hydrodynamics), biomass retention and distribution, intra-biofilm transport (diffusion), liquid-biofilm mass transfer (detachment, external mass transfer limitations), gas phase transport, and liquid–gas mass transfer. In a review of 167 granular sludge models, Baeten et al. (2019) explained chosen modelling approaches based on the different reactor types and goals wherever possible. However, they found that some assumptions appeared to be common within certain fields of research without a clear reason. Clearly defining the modelling goal is paramount to find the appropriate model complexity for a given application, and to differentiate between the many available models.

General trends and challenges

This review has presented evidence of the relevance and future significance that research, development, and implementation will play in:

- Biofilm ecology, and elucidating the functional and mechanical role of EPS
- Mitigation of greenhouse-gas emissions
- Biodegradation of micropollutants (e.g. pharmaceuticals, selenium, chlorinated solvents, fluorinated alkyl substances)
- MBBR/IFAS, aerobic granular sludge, and MBfRs/MABRs
- Biofilm and biofilm reactor modelling, particularly for multi species biofilms and the movement of biomass in the biofilm
- Biofilms on active substrata (e.g. MBfR, MABR, MXC)
- Omics tools
- Granular sludge
- Mainstream deammonification
- Biofilm in premise plumbing and risk of opportunistic pathogens.

Conclusions and research agenda

Fundamental principles describing biofilms exist as a result of focused research, practical application, and modelling. The use of reactors for the treatment of municipal and industrial wastewaters is a common beneficial use of biofilms. Applied research exists that provides a basis for the mechanistic understanding of biofilm systems. The empirical information derived from such applied research has been used to develop design criteria for biofilm reactors and remains the basis for the design of many biofilm-reactor types despite the emergence of mathematical models as reliable tools for research and practice. A gap exists between our current understanding of biofilm fundamentals and reactor-scale empirical information. Further research is needed to bridge the gap.

References

Arabgol, R., Vanrolleghem, P.A., Piculell, M. and Delatolla, R. 2020. The impact of biofilm thickness-restraint and carrier type on attached growth system performance, solids characteristics and settleability. *Environmental Science-Water Research & Technology* 6(10), 2843–2855.

Baeten J.E., Batstone D.J., Schraa O.J., van Loosdrecht M.C.M., Volcke E.I.P. (2019). Modelling anaerobic, aerobic and partial nitritation-anammox granular sludge reactors - a review. *Water Research*, 149, 322–341

Baeten J.E., van Loosdrecht M.C.M., Volcke E.I.P. (2018). Modelling aerobic granular sludge reactors through apparent half-saturation coefficients. *Water Research*, 146, 134–145.

Beun, J.J., van Loosdrecht, M.C.M. and Heijnen, J.J. 2002. Aerobic granulation in a sequencing batch airlift reactor. *Water Research* 36(3), 702–712.

Boltz, J.P., Morgenroth, E. and Sen, D. 2010. Mathematical modelling of biofilms and biofilm reactors for engineering design. *Water Science and Technology* 62(8), 1821–1836.

Boltz, J.P., Rittmann, B.E. (2021). Microbial ecology of selenium-respiring bacteria. Chap. 4 in *Environmental Technologies to Treat Selenium Pollution*. IWA Press.

Boltz, J.P., Daigger, G.T. (2022). A mobile-organic biofilm process for wastewater treatment. *Water Environment Research*, 94, 1–18.

Boltz, J.P., Rittmann, B.E. (2024). Modeling aerobic granules in continuously flowing wastewater treatment processes. *Water Environment Research*, 97, 1–14.

Boltz, J.P., Sims, R.C. (2025). *Biofilm Reactors*, 2nd Edition. Water Environment Federation, Alexandria, Virginia

Boltz, J.P., Danuser, A. Rittmann, B.E., Jimenez, J.A. (2026). Modeling wastewater treatment by mobile biofilm and activated sludge processes configured for biological nutrient removal at 10 and 20C. *Water Science and Technology*. In press.

Chomiak, A., Traber, J., Morgenroth, E., Derlon, N. (2015). Biofilm increases permeate quality by organic carbon degradation in low pressure ultrafiltration. *Water Research* 85, 512–520.

Daigger, G.T., Kuo, J., Derlon, N., Houweling, D., Jimenez, J.A., Johnson, B.R., McQuarrie, J.P., Murthy, S., Regmi, P., Roche, C., Sturm, B., Wett, B., Winkler, M., Boltz, J.P. (2023). Biological and physical selectors for mobile biofilms, aerobic granules, and densified biological flocs in continuously flowing wastewater treatment processes: A state-of-the-art review. *Water Research*, 242, 120245.

de Kreuk, M., Heijnen, J.J. and van Loosdrecht, M.C.M. (2005). Simultaneous COD, nitrogen, and phosphate removal by aerobic granular sludge. *Biotechnology and Bioengineering* 90(6), 761–769.

Ettwig, K., Butler, M., Le Paslier, D. et al. Nitrite-driven anaerobic methane oxidation by oxygenic bacteria. *Nature* 464, 543–548 (2010). https://doi.org/10.1038/nature08883

Flemming, H.C. and Wingender, J. (2010). The biofilm matrix. *Nature Reviews Microbiology* 8(9), 623–633.

Flemming, H.C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S.A. and Kjelleberg, S. (2016). Biofilms: an emergent form of bacterial life. *Nature Reviews Microbiology* 14(9), 563–575.

Gonzalez-Gil, G., Lens, P.N.L., Saikaly, P.E. (2016). Selenite reduction by anaerobic microbial aggregates: microbial community structure, and proteins associated to the produced selenium spheres. *Frontiers in Microbiology* 7, 14.

Gordon, V.D., Davis-Fields, M., Kovach, K., Rodesney, C.A. (2017). Biofilms and mechanics: a review of experimental techniques and findings. *Journal of Physics D-Applied Physics* 50(22), 12.

Guo-Jun Xie, Chen Cai, Shihu Hu, Zhiguo Yuan; Complete Nitrogen Removal from Synthetic Anaerobic Sludge Digestion Liquor through Integrating Anammox and Denitrifying Anaerobic Methane Oxidation in a Membrane Biofilm Reactor. *Environmental Science and Technology,* 17 January 2017; 51 (2): 819–827. https://doi.org/10.1021/acs.est.6b04500

Haroon, M., Hu, S., Shi, Y. et al. Anaerobic oxidation of methane coupled to nitrate reduction in a novel archaeal lineage. *Nature* 500, 567–570 (2013). https://doi.org/10.1038/nature12375

Hindson, C.M., Chevillet, J.R., Briggs, H.A., Gallichotte, E.N., Ruf, I.K., Hindson, B.J., Vessella, R.L. and Tewari, M. (2013). Absolute quantification by droplet digital PCR versus analog real-time PCR. *Nature Methods* 10(10), 1003-+.

Jafari, M., Desmond, P., van Loosdrecht, M.C.M., Derlon, N., Morgenroth, E. and Picioreanu, C. (2018). Effect of biofilm structural deformation on hydraulic resistance during ultrafiltration: A numerical and experimental study. *Water Research* 145, 375–387.

Kaiser, T., Acevedo Alonso, V., Fundneider, T., Lackner, S. (2023). The significance of granular activated carbon pore structure in modeling dissolved organic carbon removal in fixed-bed filters. *Chemical Engineering Journal* 464, 142729, https://doi.org/10.1016/j.cej.2023.142729.

Karygianni, L., Ren, Z., Koo, H., Thurnheer, T. (2020). Biofilm matrixome: extracellular components in structured microbial communities. *Trends in Microbiology* 28(8), 668-681.

Kesaano, M., Sims, R.C. (2014). Algal biofilm based technology for wastewater treatment. *Algal Research-Biomass Biofuels and Bioproducts* 5, 231–240.

Lackner, S., Gilbert, E.M., Vlaeminck, S.E., Joss, A., Horn, H. and van Loosdrecht, M.C.M. (2014). Full-scale partial nitritation/anammox experiences - An application survey. *Water Research* 55, 292–303.

Lai, Y.-J., Eustance, E., Shesh, T., Frias, Z., Rittmann, B. E. (2022). Achieving superior carbon transfer efficiency and pH control using membrane carbonation with a wide range of CO_2 contents for the coccolithophore Emiliania huxleyi. *Science of the Total Environment*, 822, 153592.

Ley, C.J., Proctor, C.R., Singh, G., Ra, K., Noh, Y., Odimayomi, T., Salehi, M., Julien, R., Mitchell, J., Nejadhashemi, A.P., Whelton, A.J. and Aw, T.G. (2020). Drinking water microbiology in a water-efficient building: stagnation, seasonality, and physicochemical effects on opportunistic pathogen and total bacteria proliferation. *Environmental Science-Water Research & Technology* 6(10), 2902–2913.

Li, M.F., Matous, K. and Nerenberg, R. (2020). Predicting biofilm deformation with a viscoelastic phase-field model: Modeling and experimental studies. *Biotechnology and Bioengineering* 117(11), 3486–3498.

Liu, S., Gunawan, C., Barraud, N., Rice, S.A., Harry, E.J., Amal, R. (2016). Understanding, monitoring, and controlling biofilm growth in drinking water distribution systems. *Environmental Science & Technology* 50(17), 8954–8976.

Logan, B.E., Hamelers, B., Rozendal, R.A., Schrorder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., Rabaey, K. 2006. Microbial fuel cells: Methodology and technology. *Environmental Science & Technology* 40(17), 5181–5192.

Long, M., Cheng, J., Zhou, C., Rittmann, B. E. (2025). Gold (Au) recovery in a hydrogen (H2)-based membrane biofilm reactor. *Resources, Conservation & Recycling* 221, 108394.

Long, M., Zheng, C., Rolda, M. A., Zhou, C., and Rittmann, B.E. (2024). Co-removal of PFOA and nitrate from water by coupling Pd catalysis with enzymatic biotransformation. *Environmental Science & Technology* 58,11514–11524.

Luo, Y., Lai, Y.-J, Zheng, C., Ilhan, Z. H., Ontiveros-Valencia, A., Long, X., Krajmalnik-Brown, R., Rittmann, B. E. (2021). Exposure to cetyltrimethylammonium bromide (CTAB) and other stress conditions increased the expression of antibiotic-resistance genes in biofilm communities. *Science of the Total Environment* 765, 144264

Lv, P.L., Zhong, L., Dong, Q.Y., Yang, S.L., Shen, W.W., Zhu, Q.S., Lai, C.Y., Luo, A.C., Tang, Y.N., Zhao, H.P. (2018). The effect of electron competition on chromate reduction using methane as electron donor. *Environmental Science and Pollution Research*, 25(7), 6609–6618.

Martin, K.J., Nerenberg, R. (2012). The membrane biofilm reactor (MBfR) for water and wastewater treatment: Principles, applications, and recent developments. *Bioresource Technology* 122, 83–94.

Martin, K.J., Picioreanu, C., Nerenberg, R. 2013. Multidimensional modeling of biofilm development and fluid dynamics in a hydrogen-based, membrane biofilm reactor (MBfR). *Water Research* 47(13), 4739–4751.

McIlroy, S. J., Saunders, A. M., Albertsen, M., Nierychlo, M., McIlroy, B., Hansen, A. A., Karst, S. M., Nielsen, J. L., & Nielsen, P. H. (2015). MiDAS: The field guide to the microbes of activated sludge. *Database: The Journal of Biological Databases and Curation,* 2015, 1-8. Article bav062. https://doi.org/10.1093/database/bav062

McQuarrie, J.P., Boltz, J.P. (2011). Moving bed biofilm reactor technology: process applications, design, and performance. *Water Environment Research* 83(6), 560-575.

Morgenroth, E., van Loosdrecht, M.C.M., Wanner, O. (2000). Biofilm models for the practitioner. *Water Science and Technology* 41(4-5), 509–512.

Nerenberg, R. (2016). The membrane-biofilm reactor (MBfR) as a counter-diffusional biofilm process. *Current Opinion in Biotechnology* 38, 131–136.

Ossiansson, E. (2025). Ideal carbon utilisation in wastewater treatment for enhanced nutrient removal - Primary filtration with filter sludge fermentation as primary treatment for a novel biofilm process, Doctoral thesis, Chalmers, Sweden

Pellicer-Nacher, C., Sun, S.P., Lackner, S., Terada, A., Schreiber, F., Zhou, Q. and Smets, B.F. (2010). Sequential aeration of membrane-aerated biofilm reactors for high-rate autotrophic nitrogen removal: experimental demonstration. *Environmental Science & Technology* 44(19), 7628–7634.

Piculell, M., Suarez, C., Li, C., Christensson, M., Persson, F., Wagner, M., Hermansson, M., Jonsson, K. Welander, T. (2016), The inhibitory effects of reject water on nitrifying populations grown at different biofilm thickness. *Water Research* 104, 292–302

Pronk, M., de Kreuk, M.K., de Bruin, B., Kamminga, P., Kleerebezem, R. and van Loosdrecht, M.C.M. (2015). Full scale performance of the aerobic granular sludge process for sewage treatment. *Water Research* 84, 207–217.

Quast, C., Pruesse, E., Yilmaz, P., Gerken, J., Schweer, T., Yarza, P., Peplies, J., Glockner, F.O. (2013). The SILVA ribosomal RNA gene database project: improved data processing and web-based tools. *Nucleic Acids Research* 41(D1), D590–D596.

Raghoebarsing AA, Pol A, van de Pas-Schoonen KT, Smolders AJ, Ettwig KF, Rijpstra WI, Schouten S, Damsté JS, Op den Camp HJ, Jetten MS, Strous M. A microbial consortium couples anaerobic methane oxidation to denitrification. *Nature*. 2006 Apr 13;440(7086):918-21. doi: 10.1038/nature04617. PMID: 16612380.

Ritmmann, B., McCarty, P. (2020) *Environmental Biotechnology: Principles and Applications*, 2nd ed., McGraw-Hill.

Rittmann, B.E. (2018). Biofilms, active substrata, and me. *Water Research* 132, 135–145.

Rittmann, B.E., Boltz, J.P., Brockmann, D., Daigger, G.T., Morgenroth, E., Sorensen, K.H., Takacs, I., van Loosdrecht, M. and Vanrolleghem, P.A. (2018). A framework for good biofilm reactor modeling practice (GBRMP). *Water Science and Technology* 77(5), 1149–1164.

Sabba, F., Picioreanu, C., Perez, J., Nerenberg, R. (2015). Hydroxylamine diffusion can enhance N_2O emissions in nitrifying biofilms: A modeling study. *Environmental Science & Technology* 49(3), 1486–1494.

Sabba, F., Terada, A., Wells, G., Smets, B.F., Nerenberg, R. (2018). Nitrous oxide emissions from biofilm processes for wastewater treatment. *Applied Microbiology and Biotechnology* 102, 9815–9829.https://doi.org/10.1007/s00253-018-9332-7

Saltnes, T., Sørensen, G., Eikås, S., (2017). Biological nutrient removal in a continuous biofilm process. *Water Practice & Technology* 12, 797–805.

Santillan, E., Seshan, H., Constancias, F., Wuertz, S. (2019). Trait-based life-history strategies explain succession scenario for complex bacterial communities under varying disturbance. *Environmental Microbiology* 21(10), 3751–3764.

Schramm, A. (2003). In situ analysis of structure and activity of the nitrifying community in biofilms, aggregates, and sediments. *Geomicrobiology Journal* 20(4), 313–333.

Seviour, T., Derlon, N., Dueholm, M.S., Flemming, H.C., Girbal-Neuhauser, E., Horn, H., Kjelleberg, S., van Loosdrecht, M.C.M., Lotti, T., Malpei, M.F., Nerenberg, R., Neu, T.R., Paul, E., Yu, H.Q., Lin, Y.M. (2019). Extracellular polymeric substances of biofilms: Suffering from an identity crisis. *Water Research* 151, 1–7.

Shen, Y., Monroy, G.L., Derlon, N., Janjaroen, D., Huang, C.H., Morgenroth, E., Boppart, S.A., Ashbolt, N.J., Liu, W.T., Nguyen, T.H. (2015). Role of biofilm roughness and hydrodynamic conditions in Legionella pneumophila adhesion to and detachment from simulated drinking water biofilms. *Environmental Science & Technology* 49(7), 4274–4282.

Syron, E., Casey, E. (2008). Membrane-aerated biofilms for high rate biotreatment: Performance appraisal, engineering principles, scale-up, and development requirements. *Environmental Science & Technology* 42(6), 1833–1844.

Tierra, G., Pavissich, J.P., Nerenberg, R., Xu, Z., Alber, M.S. (2015). Multicomponent model of deformation and detachment of a biofilm under fluid flow. *Journal of the Royal Society Interface* 12(106), 20150045.

Torresi, E., Fowler, S.J., Polesel, F., Bester, K., Andersen, H.R., Smets, B.F., Plosz, B.G. and Christensson, M. (2016). Biofilm thickness influences biodiversity in nitrifying MBBRs-implications on micropollutant removal. *Environmental Science & Technology* 50(17), 9279–9288.

Veuillet, F., Lacroix, S., Bausseron, A., Gonidec, E., Ochoa, J., Christensson, M., Lemaire, R. (2014). Integrated fixed-film activated sludge ANITA (TM) Mox process - a new perspective for advanced nitrogen removal. *Water Science and Technology* 69(5), 915–922.

Vrouwenvelder, J.S., van Paassen, J.A.M., Wessels, L.P., van Dama, A.F. and Bakker, S.M. (2006). The membrane fouling simulator: A practical tool for fouling prediction and control. *Journal of Membrane Science* 281(1-2), 316–324.

Wang, J.F., Liu, W., Liu, T.Z. (2017). Biofilm based attached cultivation technology for microalgal biorefineries-A review. *Bioresource Technology* 244, 1245–1253.

Wingender, J., Flemming, H.C. (2011). Biofilms in drinking water and their role as reservoir for pathogens. International *Journal of Hygiene and Environmental Health* 214(6), 417–423.

Zhang, P., Chen, Y.P., Qiu, J.H., Dai, Y.Z., Feng, B. (2019). Imaging the microprocesses in biofilm matrices. *Trends in Biotechnology* 37(2), 214–226.

Zheng, C.-W., Luo, Y.-H., Long, X.,Gu, H., Cheng, J., Zhang, L., Lai, Y.-J., and Rittmann, B. E. (2023). The structure of biodegradable surfactants shaped the microbial community, antimicrobial resistance, and potential for horizontal gene transfer. *Water Research* 236, 119944.

Zheng, C.-W., Luo, Y.-H., Eustance, E., Suzuki, M., Collins, H., Lai, Y.-J. S., Rittmann, B. E. (2025). Advanced intermittent air delivery in a membrane biofilm reactor achieves full biodegradation of a quaternary ammonium compound. *Chemical Engineering Journal* 509, 161301.

Zhou, C., Ontiveros-Valencia, A., Nerenberg, R., Tang, Y.N., Friese, D., Krajmalnik-Brown, R., Rittmann, B.E. (2019). Hydrogenotrophic microbial reduction of oxyanions with the membrane biofilm reactor. *Frontiers in Microbiology* 9.

| 3.3 |

Harnessing artificial intelligence for measuring sanitation sustainability in low- and middle-income countries: pathways towards data-driven equity and resilience

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Introduction

Access to safe and sustainable sanitation is a fundamental human right and a cornerstone of public health, economic development, and environmental integrity. However, as of 2020, 3.6 billion people still lacked safely managed sanitation services, a deficit that perpetuates cycles of disease, poverty, and inequality, particularly in low- and middle-income countries (LMICs) (Hashemi, 2020). The United Nations' Sustainable Development Goal 6 (SDG6), which aims to ensure the availability and sustainable management of water and sanitation for all by 2030, highlights the global urgency of this challenge (Hashemi, 2020; United Nations, 2021; World Health Organization, 2019). This issue is profoundly exacerbated by the increasing frequency and intensity of climate-related hazards, such as floods and droughts, which devastate fragile sanitation infrastructure, contaminate water sources, and trigger disease outbreaks (Han et al., 2016; Kim et al., 2016; Shah et al., 2023; Zakaria et al., 2018).

Traditional methods for monitoring sanitation systems and assessing their sustainability are often slow, resource-intensive, and reactive, and struggle to keep pace with the dynamic interplay of climatic, social, and technical pressures on sanitation systems. In this context, the convergence of artificial intelligence (AI) and a new generation of data-gathering technologies presents a transformative opportunity. By leveraging AI to process vast and varied datasets, including satellite imagery, real-time sensor readings, and social media feeds, we can move towards a new paradigm of sanitation management that is predictive, proactive, and targeted in nature.

This chapter examines how AI, when integrated with robust evaluation frameworks, can revolutionise the measurement of sanitation sustainability in LMICs, paving the way for data-driven strategies that deliver more equitable and resilient services to the world's most vulnerable communities.

Despite significant advances in AI and digital technologies for environmental monitoring, their systematic application to assess and enhance sanitation sustainability remains underexplored, particularly in LMICs. Existing studies have largely focused on isolated components, such as water quality prediction or flood mapping, without integrating these innovations into holistic frameworks that capture the multidimensional nature of sanitation systems (Monachese et al., 2024; Yu et al., 2023). This chapter aims to address this gap by conceptualising pathways for integrating AI with established sustainability assessment frameworks, such as the Sanitation Sustainability Index (SSI) (Hashemi, 2020), to enable predictive, equitable, and adaptive sanitation management. The scope of this study is primarily conceptual, drawing on existing evidence to propose an integrated framework and actionable recommendations for policymakers, practitioners, and researchers, rather than presenting empirical modelling or field-based validation.

Foundational terms and technologies for AI-driven sanitation systems

Artificial Intelligence (AI): A broad field of computer science concerned with creating systems capable of performing tasks that typically require human intelligence. In this context, it primarily refers to machine learning (ML), a subset of AI in which algorithms are trained on data to identify patterns, make predictions, and support decision-making without being explicitly programmed for each task. This includes data-driven models that can forecast flood impacts or assess sanitation system failures (Girotto et al., 2024).

Earth observation (EO): The gathering of information about the Earth's physical, chemical, and biological systems via remote-sensing technologies, primarily satellites, but also

including aircraft and drones. EO provides large-scale data on land use, water quality, infrastructure, and hazard monitoring (Shah et al., 2023).

Sanitation Sustainability Index (SSI): A community-based indicator developed to evaluate the sustainability of different sanitation options before their implementation. It is composed of technical, economic, and social sub-indices with dimensionless variables (e.g. water efficiency, maintenance costs, public health, and acceptability) that are measured against the community's current norms, making the index flexible and replicable across different contexts (Hashemi, 2020).

Water, sanitation, and hygiene (WASH): A collective term for the interrelated public health issues of access to clean water, adequate sanitation, and proper hygiene practices. Poor WASH services are a leading cause of preventable diseases (Girotto et al., 2024; Han et al., 2016; Zakaria et al., 2018).

Early warning system (EWS): An integrated system of hazard monitoring, forecasting, risk assessment, and communication that enables individuals, communities, and authorities to take timely action to reduce disaster risks before a hazardous event occurs (Girotto et al., 2024).

Internet of things (IoT): A network of physical devices ("things") embedded with sensors, software, and other technologies to connect and exchange data with other devices and systems over the internet. In sanitation, this includes smart sensors for real-time monitoring of water levels, flow, and quality (Girotto et al., 2024).

Emerging trends in data-driven sanitation management

The convergence of AI with new data sources is generating critical new trends that are reshaping our ability to monitor, measure, and manage sustainable sanitation.

The rise of remote monitoring with Earth observation

Earth observation has emerged as a powerful tool for large-scale environmental monitoring. A systematic review of its applications revealed three primary uses relevant to WASH: monitoring surface water quality, sensing groundwater, and mapping hazards and infrastructure (Shah et al., 2023). As described by Shah et al. (2023), satellites such as LANDSAT and Sentinel provide invaluable data for assessing the impact of disasters on water resources. However, this body of research exposes a critical gap: the vast majority of studies focus on water, with a stark lack of research on the specific use of EO for monitoring sanitation infrastructure and services. Furthermore, research is disproportionately concentrated in North America, Europe, and Asia, with dangerously few studies focused on Africa and Oceania, which have high vulnerability and significant disaster risk. AI offers a pathway to bridge this gap by developing algorithms capable of identifying and classifying dispersed sanitation facilities from high-resolution imagery, thereby enabling large-scale and cost-effective monitoring where it is needed most (Shah et al., 2023).

The imperative for standardised, context-specific measurement frameworks

Although global indices exist to track national sanitation progress, they often operate at a scale that is too coarse for local decision-making. The development of tools such as the SSI marks a crucial shift towards standardised and context-specific frameworks (Hashemi, 2020). The SSI evaluates sanitation options across technical, economic, and social dimensions using variables benchmarked against existing community norms. This approach provides a nuanced, multifaceted score that reflects local realities. Such structured frameworks are essential in the age of AI. They provide clear, defined, and quantifiable variables needed to train ML models and translate complex data streams into actionable insights regarding sustainability. Without a robust framework such as SSI, AI-driven analysis risks producing outputs that are technologically impressive but practically irrelevant (Hashemi, 2020).

The convergence of real-time data and predictive analytics

The data collection landscape for disaster risk reduction is rapidly transforming. While well-established technologies such as station-based sensors and satellite products remain important, they are being augmented by a new wave of cutting-edge, real-time data sources, including low-cost IoT sensors, the internet of drones (IoD), and social media data mining. These technologies provide a dynamic, high-frequency picture of on-the-ground conditions that were previously unattainable. This surge in data availability is fuelling the adoption of AI-driven models. Instead of merely mapping past events, ML algorithms can provide real-time forecasts of infrastructural disruption, water flow, and potential system failures. This represents a fundamental shift in sanitation management from a reactive posture of post-disaster repair to a proactive strategy of predictive maintenance and risk mitigation (Girotto et al., 2024). This technological evolution is summarised in Figure 3.5, which provides a clear comparative overview of the shift from well-established technologies to cutting-edge digital tools that are currently augmenting EWS (Girotto et al., 2024).

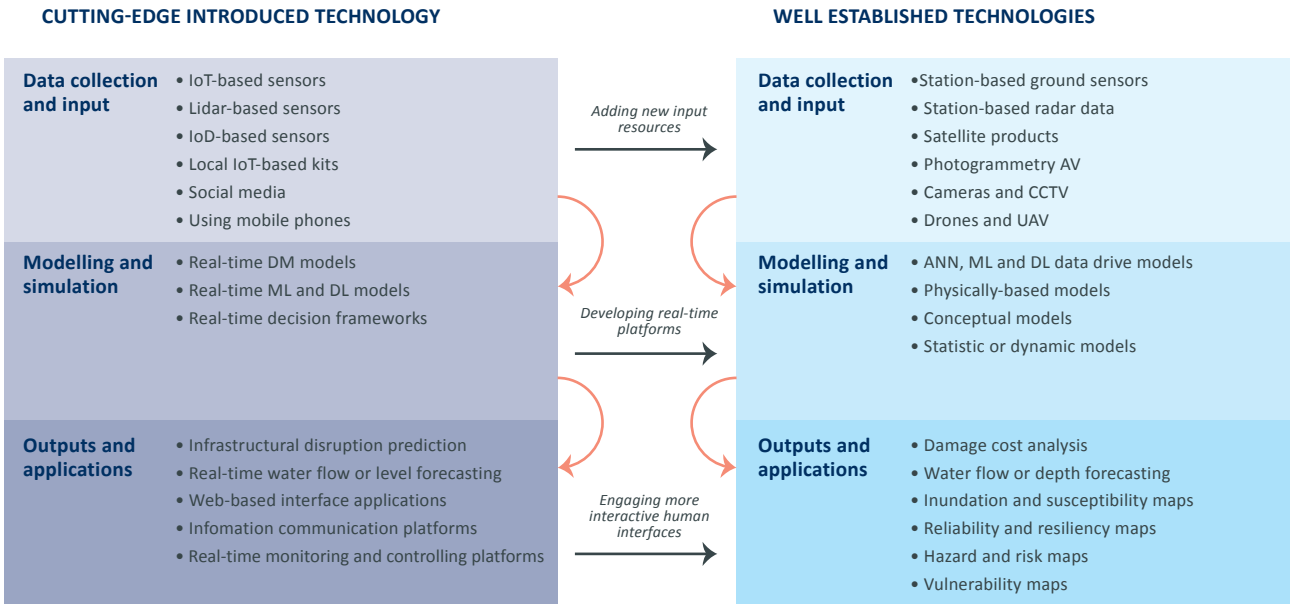


Figure 3.5: Overview of new trends in cutting-edge digital innovation compared with well-established digital technologies used for EWS (Girotto et al., 2024).

Enhancing stakeholder engagement through advanced digital visualisation

Effective sanitation management is not a purely technical exercise; it requires the active engagement of all stakeholders, from national authorities to local communities. Historically, the outputs of risk assessments have often been static, and technical maps designed for experts (Girotto et al., 2024). Today, a key trend is the use of more interactive and intuitive communication platforms, including web-based interfaces and advanced visualisation tools such as augmented reality (AR), virtual reality (VR), and digital twins. These technologies can translate complex data into immersive experiences, helping non-experts visualise risks, understand the potential impacts of system failures, and participate more meaningfully in planning and response efforts (Girotto et al., 2024). By making data accessible and relatable, these tools can build community trust and foster the collective action essential for resilient WASH services, directly influencing crucial social factors such as the "Acceptability" variable within the SSI (Hashemi, 2020).

The interactions among EO, IoT, community data, and AI can be conceptualised within a unified framework that supports sustainability assessment through SSI. Figure 3.6 presents this integrated system, illustrating how diverse data streams converge through AI analytics to inform evidence-based decision-making for equitable and resilient sanitation management in LMICs.

These emerging technologies collectively demonstrate how AI and digital tools can converge to enhance the monitoring, measurement, and management of sanitation systems. The practical application of this integrated approach is demonstrated through a case study of an AI-powered EWS in a flood-prone delta.

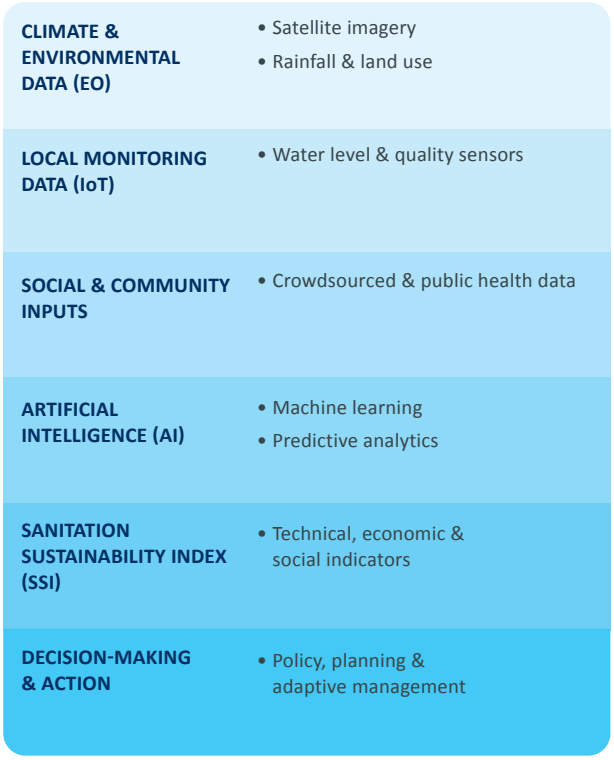


Figure 3.6: Conceptual framework for AI-enabled sanitation sustainability assessment in low- and middle-income countries (LMICs)

Case study: An AI-powered EWS for sanitation resilience in a flood-prone delta

Case definition

In Southeast Asia, rural areas and coastal communities in densely populated river deltas are highly vulnerable to seasonal cyclones and flooding. This situation exemplifies a water-related climatic hazard. In the absence of a sewerage system, these communities rely on a patchwork of sanitation solutions, including septic tanks and pit latrines, which are often inundated during floods. This leads to widespread contamination of drinking water sources and recurring outbreaks of waterborne diseases, such as cholera and typhoid fever. Traditional disaster responses are reactive and often arrive after contamination has occurred (Girotto et al., 2024; Kim et al., 2016).

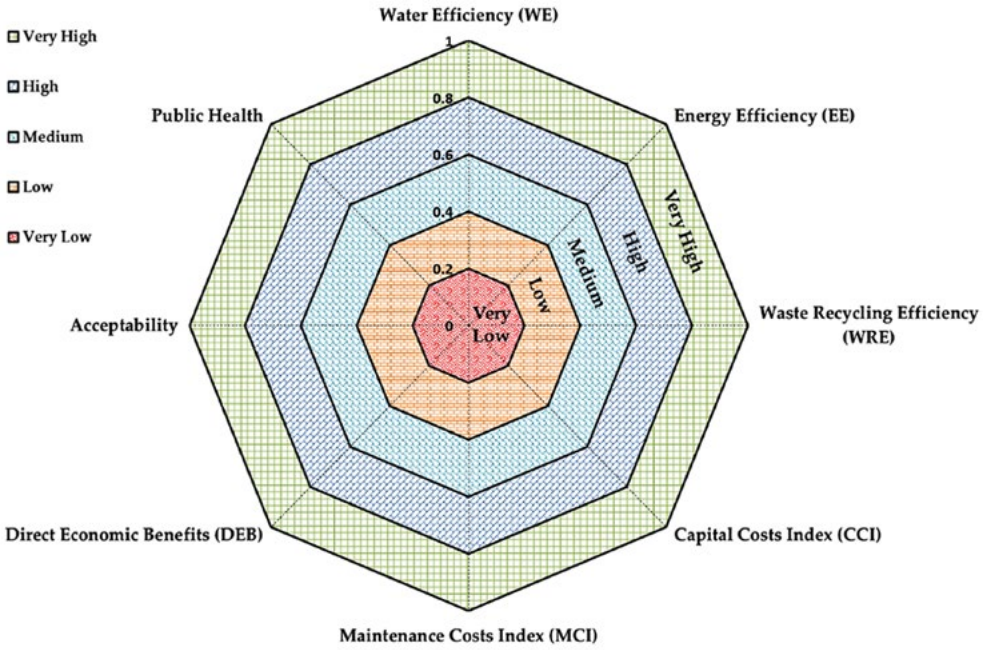


Figure 3.7. Structure of the Sanitation Sustainability Index and its evaluation criteria (Hashemi, 2020)

The Integrated AI-SSI Platform

To illustrate how the proposed framework could be operationalised in an LMIC context, this section presents a hypothetical implementation scenario for an AI-powered EWS designed to strengthen sanitation resilience in a flood-prone delta. The multifaceted structure of the SSI, shown in Figure 3.7, provides the quantifiable variables needed for the AI to assess risk across technical, economic, and social dimensions, including water efficiency, capital costs, and public health (Hashemi, 2020).

To perform this assessment, AI processes specific, quantifiable data for each variable in the SSI framework. Table 3.3 illustrates how these variables are defined and measured across different sanitation systems, forming the data foundation for sustainability assessment (Hashemi, 2020).

The system integrates multiple data streams and analytical layers as follows:

BASELINE MAPPING (EO LAYER)

Using Sentinel-1's Synthetic Aperture Radar (SAR), which can penetrate cloud cover, the system generates a high-resolution baseline map of all sanitation facilities. An ML image-recognition model is trained to classify facility types and assess their structural vulnerability based on location (e.g. proximity to waterways and elevation) (Shah et al., 2023).

REAL-TIME MONITORING (IOT AND SOCIAL DATA LAYERS)

A network of low-cost, solar-powered IoT sensors is deployed in critical drainage channels and community wells. These sensors transmit real-time data on water level, turbidity, and electrical conductivity, which can indicate sewage contamination in rivers. Simultaneously, an AI-powered natural language processing tool continuously monitors public social media platforms. It identifies and geolocates posts containing keywords related to flooding, toilet overflows, water discolouration, or symptoms of illness, creating a "crowdsourced" map of emerging sanitation crises (Girotto et al., 2024).

Table 3.3 Example assumptions for calculating the Sanitation Sustainability Index (SSI) for two different sanitation systems (Hashemi, 2020)

Index	Variable	Unit	Sanitation system	Value
Technical	Water consumption	Litre	Septic tank	8
			Resource-oriented sanitation	1
	Energy consumption	Wh	Septic tank	5.2
			Resource-oriented sanitation	0.65
	Waste recycling efficiency	%	Septic tank	52
			Resource-oriented sanitation	90
Economic	Capital cost	US$	Septic tank	3,500.00
			Resource-oriented sanitation	5,000.00
	Annual maintenance cost		Septic tank	2,500.00
			Resource-oriented sanitation	2,200.00
	Direct economic benefits	-	Septic tank	No
			Resource-oriented sanitation	Yes
Social	Acceptability	%	Septic tank	90
			Resource-oriented sanitation	75
	Public health		Septic tank	90
			Resource-oriented sanitation	75

PREDICTIVE ANALYTICS (AI CORE)

Data from all layers is fed into a central AI engine. A predictive model is used to forecast flood inundation patterns and identify which specific sanitation facilities are at the highest risk of failure. This model goes a step further by integrating the SSI into its core evaluation framework. As a flood event approaches, the system dynamically recalculates the SSI for different zones within the community (Hashemi, 2020).

- The Public Health variable score decreases in areas where contamination is predicted, flagging them as high-risk for disease outbreaks.
- The Maintenance Cost Index (MCI) is adjusted in real time as the model predicts the number of facilities that will require repair, thereby helping to estimate immediate financial needs.
- The Acceptability variable is informed by sentiment analysis of social media data, gauging community trust, and identifying areas where public health messaging is most needed.

This platform has the potential to transform disaster management. Instead of a simple flood warning, the authorities receive a dynamic Sanitation Sustainability Risk Map. This allows for targeted pre-emptive action: mobile sanitation units and hygiene kits are dispatched to areas where failures are predicted before they occur. Health workers can issue targeted warnings to specific neighbourhoods. The case study demonstrates that the true power of AI lies not only in predicting a hazard but also in predicting its cascading impacts on a critical system, such as sanitation. It also highlights the importance of integrating technology with a robust evaluation framework, such as the SSI, to produce actionable intelligence that protects public health and promotes equity.

Developed-country reference cases for AI-enabled and sustainability-oriented sanitation management

While the integrated AI–SSI framework proposed in this article has yet to be implemented in LMICs, several examples from developed and high-income contexts offer valuable benchmarks for assessing its technical and economic feasibility. Although these cases do not directly replicate the proposed framework, they illustrate pertinent components, including comprehensive system cost accounting, digital monitoring, AI-assisted decision support, resource recovery, and operational optimisation.

Hashemi and Boudaghpour (2020) conducted a comprehensive 20-year lifetime cost analysis of two onsite sanitation systems in Seoul, Republic of Korea: a conventional septic tank system and a resource-oriented sanitation system. Their findings indicated that while the septic tank system incurred lower initial capital costs, it was associated with higher long-term operation and maintenance expenses. Conversely, the resource-oriented system demonstrated potential economic benefits through the reuse of treated urine and faeces as fertiliser or soil conditioner, as well as through agricultural production. The study concluded that a comprehensive assessment of sanitation costs should encompass pre-toilet, toilet, and post-toilet components, rather than focusing solely on toilet infrastructure.

The wastewater treatment facility in Trier, Germany, serves as an illustrative case of AI-enabled digital twin optimisation within the context of utilities in developed countries. Stadtwerke Trier has implemented a real-time decision-support system utilising artificial neural networks to optimise aeration and chemical dosing while ensuring compliance with effluent standards. The case study indicates that this system has achieved a reduction in aeration energy consumption exceeding 20%, equating to approximately 200,000 kWh per year in energy savings (Xylem Inc., 2025).

The Køge-Egnens wastewater treatment plant in Denmark implemented a digital solution to improve nitrogen removal and increase hydraulic capacity during wet-weather events. The feasibility study and implementation showed that intelligent control could increase hydraulic capacity by at least 35% and up to 60%, while also improving nitrogen removal and reducing the need for costly physical expansion (Køge Municipal, 2024).

The Gresham Wastewater Treatment Plant in Oregon, USA, illustrates how resource recovery and energy optimisation can reduce lifecycle costs in sanitation and wastewater systems. The plant uses anaerobic digestion, fats-oils-and-grease co-digestion, combined heat and power, and solar energy to achieve net-zero energy operation. Reported project information indicates a total project cost of approximately US$9.1 million and yearly energy savings of around US$500,000 (Moldal, 2018).

The cases presented elucidate four critical lessons pertinent to future implementation in LMICs.

1. Comprehensive system accounting is imperative, as focusing solely on the toilet or treatment unit may lead to a misrepresentation of the actual costs and benefits associated with sanitation systems.

2. The integration of artificial intelligence and digital twins can significantly reduce operational expenses by optimising energy-intensive processes, such as aeration and chemical dosing.

3. Resource recovery has the potential to transform sanitation from a service that solely incurs costs into a system that generates both economic and environmental value.

4. Experience from developed countries indicates that implementation costs should encompass not only hardware and software but also data systems, staff capacity, monitoring, maintenance, cybersecurity, and the replacement of long-term assets (Sikorski et al., 2022).

Policy, practice, and research recommendations

In light of these insights, the following recommendations are proposed to leverage AI to enhance sanitation sustainability in LMICs.

Policymakers and development partners should prioritise investment in data infrastructure by establishing national and regional open data platforms for environmental and public health information. Additionally, they should support public-private partnerships to implement cost-effective IoT sensor networks in vulnerable catchment areas. It is imperative to integrate multidimensional sustainability frameworks, such as SSI, into national WASH strategies and disaster risk reduction plans to ensure that interventions are evaluated using comprehensive measures of success (Hashemi, 2020). Furthermore, fostering inter-agency collaboration is essential, which can be achieved by dismantling silos between environmental, health, and disaster management agencies, and forming joint task forces to manage an integrated EWS that explicitly connects climate hazards to sanitation and health outcomes, thereby addressing documented challenges in communication and integration (Shah et al., 2023).

Technology developers and the private sector should focus on creating context-appropriate technologies that are affordable, durable, and low maintenance, featuring intuitive user interfaces requiring minimal technical expertise. They should prioritise the development of sanitation-specific AI models by investing in research and development (R&D) to create ML tools capable of detecting and classifying sanitation infrastructure from satellite and drone imagery, thereby addressing critical research gaps (Shah et al., 2023). Embracing co-design principles is crucial, involving direct collaboration with local communities, utilities, and governments throughout the development lifecycle to ensure that solutions are culturally appropriate, meet genuine needs, build local capacity, and establish trust.

Researchers and academic institutions should focus on integrated systems research that transcends isolated technology studies to explore how EO, IoT, and AI can be cohesively integrated (Shah et al., 2023). Models should be validated with real-world data by rigorously testing predictive models against often incomplete datasets from diverse LMIC contexts to enhance accuracy and reliability. Additionally, advanced dynamic sustainability assessment methods that integrate real-time data streams with frameworks such as SSI should be developed to create tools capable of measuring resilience under stress and guiding adaptive management.



1. Satellites are bound by their orbit:

- Can gather data/imagery spanning large expanses;
- Repeat paths means a complete picture can be built up / changes can be easily identified;
- Lack high resolution imagery of smaller events.

2. GIS used to map and analyse incoming data:

- Can assist with analysis of large areas of data from satellites and supplement wit targeted, potentially higher resolution data from UAVs/drones.

3. UAVs/Drones can get much closer to the objects it is capturing data from, and have controllable flight paths:

- High resolution data from areas of difficult terrain or partial cover. Flight path can be suited to the exact scenario;
- Short range might rule out use in larger disaster scenarios;
- Lack of consistent regulation means neighbouring territories can have different rules regarding use over private land and data sharing.

Figure 3.8: Illustration of the role of Earth Observation in supporting WASH provision post-disaster. (Shah et al., 2023).

Figure 3.8 provides a conceptual model for this type of integrated system, illustrating how large-scale satellite data can inform targeted drone deployment, with all data synthesised through a central GIS platform to guide effective WASH responses (Shah et al., 2023).

For the prospective implementation of the AI–SSI framework in LMICs, it is imperative to evaluate application costs through a comprehensive whole-system lifecycle approach. The Seoul onsite sanitation study illustrates that restricting economic assessments to the toilet unit alone can lead to skewed decision-making, as pre-toilet and post-toilet infrastructure, along with operation, maintenance, disposal, and reuse benefits, significantly influence long-term performance (Hashemi, 2020; Hashemi & Boudaghpour, 2020; Hashemi & Han, 2019). Similarly, studies on IoT sewer-monitoring indicate that factors such as sensor acquisition, installation, batteries, and device placement must be explicitly considered when designing cost-effective monitoring networks (Sikorski et al., 2022). Therefore, forthcoming pilot projects should evaluate both the costs associated with traditional sanitation and those related to digital systems, including data, hardware, software, institutional capacity, and long-term maintenance. Table 3.4 presents a list of cost categories pertinent to the implementation of AI–SSI.

Table 3.4 Suggested application-cost categories for AI–SSI implementation.

Application-Cost Category	Examples
Baseline assessment	Community surveys, sanitation mapping, hazard mapping, existing infrastruc-ture assessment
Data acquisition	Satellite imagery, drone surveys, household surveys, public-health records, hydrometeorological data
IoT hardware	Water-level sensors, turbidity sensors, conductivity sensors, flow meters, power supply, protective casing
Sensor installation	Labour, calibration, site preparation, mounting structures, safety measures
Connectivity	GSM, LoRaWAN, Wi-Fi, satellite communication, data transmission fees
Computing infrastructure	Cloud storage, edge devices, servers, backup systems
AI/ML development	Model design, training datasets, annotation, validation, bias testing, updating
Software and dashboards	GIS platform, visualisation tools, risk dashboards, user interfaces, mobile alerts
Cybersecurity and data governance	Privacy protection, encryption, access control, data-sharing agreements
Capacity building	Training for local operators, municipal staff, health workers, and community representatives
Operation and mainte-nance	Sensor cleaning, replacement, calibration, software updates, field inspections
Energy supply	Batteries, solar panels, grid electricity, backup power
Regulatory compliance	Permits, environmental monitoring, public-health reporting
Community engagement	Co-design workshops, public communication, trust-building, behaviour-change activities
Emergency response link-age	Hygiene kits, mobile sanitation units, response logistics, health-warning dis-semination
Replacement and depreciation	Sensor lifespan, hardware renewal, software licensing, equipment upgrades
End-of-life and disposal	E-waste disposal, construction waste, decommissioning of obsolete equipment
Benefits and avoided costs	Reduced disease burden, avoided flood damage, reduced emergency repair costs, recovered nutrients, water reuse, energy savings

Limitations

While this chapter introduces an innovative conceptual framework for integrating AI with sustainability assessment in sanitation systems, several limitations warrant acknowledgment.

First, the analysis is predominantly conceptual and relies on secondary data from the existing literature rather than empirical validation. Consequently, the proposed framework has not yet been tested under real-world operational conditions, particularly within the diverse socio-technical contexts of LMICs.

Second, although this study underscores the potential of integrating EO, IoT, and social data, the availability, quality, and interoperability of these datasets remain inconsistent across regions, potentially constraining implementation.

Third, the discussion does not comprehensively address the full spectrum of data governance and ethical considerations, such as privacy, data ownership, and algorithmic bias, which are critical to ensuring equitable and responsible use of AI.

Finally, contextual variability, including institutional capacity, infrastructure reliability, and community engagement, may influence the feasibility and effectiveness of this approach. These factors should be carefully considered when interpreting the conceptual findings and translating them into practice.

Overall, the proposed AI–SSI framework has yet to undergo field testing in LMICs. Consequently, the cases from developed countries discussed in this article should be regarded as illustrative examples for individual components, such as lifecycle cost analysis, digital monitoring, AI-based optimisation, and resource recovery, rather than as direct evidence of the full framework's implementation in LMIC sanitation systems.

Conclusions

Achieving sustainable sanitation for all amid accelerating climate change remains one of the most urgent global challenges. While AI is not a universal solution, it is a powerful enabler that can transform how sanitation systems are monitored, evaluated, and managed. The integration of AI with EO, IoT technologies, and sustainability frameworks such as the SSI offers a clear pathway to proactive, predictive, and equitable sanitation management, as an essential step towards realising SDG6. By harnessing these data-driven ecosystems, decision-makers can move beyond reactive responses to build resilient and inclusive sanitation services that protect public health and ensure no community is left behind.

References

Girotto, C. D., Piadeh, F., Bkhtiari, V., Behzadian, K., Chen, A. S., Campos, L. C., & Zolgharni, M. (2024). A critical review of digital technology innovations for early warning of water-related disease outbreaks associated with climatic hazards. *International Journal of Disaster Risk Reduction*, 100, 104151. https://doi.org/10.1016/j.ijdrr.2023.104151

Han, M., Hashemi, S., Joo, S. H., & Kim, T. (2016). Novel integrated systems for controlling and prevention of mosquito-borne diseases caused by poor sanitation and improper water management. *Journal of Environmental Chemical Engineering*, 4(4), 3718–3723. https://doi.org/10.1016/j.jece.2016.08.013

Hashemi, S. (2020). Sanitation Sustainability Index: A Pilot Approach to Develop a Community-Based Indicator for Evaluating Sustainability of Sanitation Systems. *Sustainability*, 12(17), 6937. https://doi.org/10.3390/su12176937

Hashemi, S., & Boudaghpour, S. (2020). Economic analysis and probability of benefit of implementing onsite septic tank and resource-oriented sanitation systems in Seoul, South Korea. *Environmental Technology & Innovation*, 18, 100762. https://doi.org/10.1016/j.eti.2020.100762

Hashemi, S., & Han, M. (2019). Field evaluation of the fertilizing potential of biologically treated sanitation products. *Science of the Total Environment*, 650, 1591–1598. https://doi.org/10.1016/j.scitotenv.2018.09.009

Kim, Y., Hashemi, S., Han, M., Kim, T., & Sohn, H.-G. (2016). The waterless portable private toilet: an innovative sanitation solution in disaster zones. *Disaster Medicine and Public Health Preparedness*, 10(2), 281–285. https://doi.org/10.1017/dmp.2015.166

Køge Municipal. (2024, October). *KØGE, DENMARK Case Study.* Hubgrade. https://www.veoliawatertechnologies.com/sites/g/files/dvc2476/files/document/2024/10/2024-koge-hubgrade-case-studies_1.pdf

Moldal, D. (2018). *Gresham Wastewater Treatment Plant Net Zero Energy Use with CHP 790-kW CHP System*. CHP Technical Assistance Partnerships. https://chptap.ornl.gov/profile/90/Gresham_WWTF-Project_Profile.pdf

Monachese, A. P., Gómez-Villarino, M. T., López-Santiago, J., Sanz, E., Almeida-Ñauñay, A. F., & Zubelzu, S. (2024). Challenges and Innovations in urban drainage systems: sustainable drainage systems focus. *Water*, 17(1), 76. https://doi.org/10.3390/w17010076

Shah, A., Kantamaneni, K., Ravan, S., & Campos, L. C. (2023). A systematic review investigating the use of earth observation for the assistance of water, sanitation and hygiene in disaster response and recovery. *Sustainability*, 15(4), 3290. https://doi.org/10.3390/su15043290

Sikorski, A., Solano Donado, F., & Kozdrowski, S. (2022). Cost-efficient coverage of wastewater networks by IoT monitoring devices. *Sensors*, 22(18), 6854. https://doi.org/10.3390/s22186854

United Nations. (2021). *The Sustainable Development Goals Report 2021*. United Nations Publications. https://unstats.un.org/sdgs/report/2021/The-Sustainable-Development-Goals-Report-2021.pdf

World Health Organization. (2019). *Water, sanitation, hygiene and health: a primer for health professionals*. https://www.who.int/publications/i/item/WHO-CED-PHE-WSH-19.149

Xylem Inc. (2025, June). *Optimization of wastewater treatment plant processes with the help of artificial intelligence*. Xylem Inc. https://swan-forum.com/wp-content/uploads/2025/12/stadwerke-trier-cs-ww-xylem-vue-en.pdf

Yu, J., Zou, L., Xia, J., Chen, X., Wang, F., & Zuo, L. (2023). A multi-dimensional framework for improving flood risk assessment: Application in the Han River Basin, China. *Journal of Hydrology: Regional Studies*, 47, 101434. https://doi.org/10.1016/j.ejrh.2023.101434

Zakaria, F., Ćurko, J., Muratbegovic, A., Garcia, H. A., Hooijmans, C. M., & Brdjanovic, D. (2018). Evaluation of a smart toilet in an emergency camp. *International Journal of Disaster Risk Reduction*, 27, 512–523. https://doi.org/10.1016/j.ijdrr.2017.11.015

| 3.4 |

Metals and related substances in drinking water systems: risk, resilience, and mitigation pathways

Authors: *Prosun Bhattacharya, on behalf of the IWA Specialist Group on Metals and Related Substances in Drinking Water*

Introduction

Metals, metalloids, and related inorganic substances in drinking water continue to pose major challenges to water safety and public health worldwide. The IWA Specialist Group on Metals and Related Substances in Drinking Water (METRELS) addresses risks associated with both naturally occurring (geogenic) and anthropogenic inorganic constituents, including arsenic (As), manganese (Mn), fluoride, iron (Fe), lead (Pb), chromium (Cr), uranium (U), and other metal-related substances of increasing health and regulatory concern (Bhattacharya et al. 2002; Mukherjee et al. 2024; Ligate et al., 2026).

Groundwater supplies drinking water to nearly half of the global population and to a substantially higher proportion in low- and middle-income countries. In many regions, elevated metal concentrations arise from natural water–rock interactions, often compounded by intensive groundwater abstraction, land-use change, and limitations in water-supply infrastructure. Chronic exposure to metals and related substances through drinking water is associated with cancers, neurological impairment, cardiovascular disease, dental and skeletal fluorosis, kidney damage, and adverse developmental outcomes (Kapaj et al., 2006; Ali et al., 2019). These risks are unevenly distributed, disproportionately affecting rural populations, women, children, and socio-economically marginalised communities (Singh et al., 2005).

Surface waters supply a substantial share of urban drinking water and are exposed to a wider spectrum of metal inputs than groundwater, including cadmium, chromium, mercury, nickel, zinc, copper, manganese, and iron from mining and smelting, industrial effluents, agricultural runoff, urban stormwater, and atmospheric deposition (Zhou et al., 2020; Macklin et al., 2023). Globally, surface-water metal contamination has shifted from single-metal point-source loading to mixed-metal pollution, and the dominant source categories have shifted from mining and manufacturing to rock weathering and waste discharge over the past five decades (Zhou et al., 2020). Sediments act as long-term internal stores, with metals remobilised by shifts in pH, redox potential, or salinity driven by seasonal turnover, flooding, or eutrophication (Eggleton and Thomas, 2004), so that historical contamination remains relevant decades after primary discharges cease (Macklin et al., 2023). Notable cases include hexavalent chromium, Cr(VI), from electroplating and leather tanning industries (Saha et al., 2011), mercury contamination of river catchments affected by artisanal and small-scale gold mining (Esdaile and Chalker, 2018), and the polymetallic Pb–Zn–Cd–As legacy of historical silver and tin mining in the Río Pilcomayo basin, Bolivia (Miller et al., 2004). Climate-driven changes in flow regime, temperature, and water residence time further alter speciation and bioavailability (Noyes et al., 2009), complicating both source protection and treatment design.

Lead and copper enter drinking water primarily through corrosion of service lines, premise plumbing, solders, and brass fittings, with leaching governed by water pH, alkalinity, dissolved inorganic carbon, temperature, stagnation time, and the choice of disinfectant (Edwards and Dudi, 2004; Schock, 1989). The 2014–2015 Flint (Michigan, USA) crisis showed how a switch in source water without adequate orthophosphate-based corrosion control destabilised protective scales on lead service lines, producing household values that rose sequentially to 707 µg/L and exceeded 5,000 µg/L under higher-flow conditions at the “Ground Zero” home (Pieper et al., 2017), while city-wide citizen-science sampling yielded a 90th-percentile lead concentration of 26.8 µg/L — nearly double the federal action level of 15 µg/L (Pieper et al., 2018). Chronic low-level lead exposure is associated with irreversible neurodevelopmental effects in children and with cardiovascular and renal disease in adults, while elevated copper causes acute gastrointestinal effects and, with prolonged exposure, hepatic injury in susceptible groups (ATSDR, 2020, 2022).

Aluminum-based coagulants – aluminum sulfate (alum), sodium aluminate, and pre-hydrolyzed polyaluminum chlorides – are the dominant reagents worldwide for removing turbidity, natural organic matter, and pathogens from surface water, and their use can elevate aluminum concentrations in finished water (WHO, 2010; Edzwald, 2020). Residual aluminum is controlled by coagulation pH, coagulant dose, and speciation, mixing energy, and filtration performance; poor optimisation allows monomeric and colloidal Al species to pass into distribution (Krupińska, 2020). Accumulation of aluminum on pipe walls contributes to post-coagulation floc release, turbidity spikes, and loss of hydraulic capacity, while episodic remobilisation can cause visible discoloration for consumers. A health-based value of 0.9 mg/L can be derived from the Joint FAO/WHO Expert Committee on Food Additives (JECFA) provisional tolerable weekly intake, but this substantially exceeds the concentrations achievable through coagulation optimisation; WHO therefore specifies practicable performance levels of ≤0.1 mg/L for large facilities and ≤0.2 mg/L for small ones in place of a formal guideline value, framing aluminum management as a treatment-optimisation rather than a toxicological problem (WHO, 2010, 2022).

Climate change further amplifies these challenges by altering hydrological regimes, recharge patterns, and subsurface geochemical conditions. Prolonged droughts, extreme rainfall events, and salinisation influence the mobilisation, transport, and persistence of metals in drinking-water sources, increasing spatial and temporal variability and complicating compliance-based management approaches. Addressing metals and related substances in drinking water, therefore, requires risk-based, preventive, and integrated approaches that move beyond end-of-pipe treatment towards a systemic understanding of sources, pathways, and exposure.

This contribution aligns with the Compendium theme Water, Sanitation, and Public Health, supporting SDG 6 (Clean Water and Sanitation) while contributing to SDGs 3, 5, 9, 11, 13, and 17.

Scope clarification

In this contribution, *metals and related substances* refer exclusively to inorganic, metal-associated constituents in drinking water from geogenic and/or anthropogenic sources. Organic micropollutants (e.g. pharmaceuticals, PFAS, pesticides) are outside the scope of this chapter.

Key terminology

- **Geogenic contaminants:** Naturally occurring elements mobilised through water–rock interaction and subsurface biogeochemical processes.
- **Chronic exposure risk:** Health risk associated with long-term ingestion of contaminated drinking water.
- **Risk-based water safety:** Preventive management addressing hazards from source to consumer rather than reliance on compliance monitoring alone.
- **Source-based mitigation:** Reduction of exposure through aquifer targeting, abstraction control, and protection of low-risk sources.
- **Sediment colour tool:** A field-based proxy linking sediment color classes to arsenic risk for safer aquifer targeting.
- **Digital decision support:** Use of digital platforms for systematic capture, analysis, and governance of water-quality data.
- **AOCF (advanced oxidation, coagulation and filtration):** An engineered drinking-water treatment approach, developed during 2019–2020 and implemented at full scale in Dutch groundwater treatment facilities, in which oxidation, iron-based coagulation/co-precipitation, and filtration are optimised to enhance removal of arsenic and other redox-sensitive metal(loid)s.

Key insights: trends, evidence, and future outlook

Hydrogeochemical controls and variability

The occurrence and mobility of metals in drinking water are governed by interacting geological, hydrological, and biogeochemical processes (Mukherjee et al., 2009; Hasan et al., 2009). Mineral weathering, redox transformations, organic-matter dynamics, microbial activity, and groundwater residence time collectively determine whether metals remain sequestered in aquifer solids or become mobilised into groundwater (Bundschuh et al., 2010; Mukherjee et al., 2024). Climate-driven changes in recharge patterns, abstraction intensity, and flow paths increasingly modify these controls, leading to pronounced spatial and temporal variability in metal concentrations.

Redox conditions exert a particularly strong influence on the behavior of arsenic and other redox-sensitive metals in alluvial aquifers (Bhattacharya et al., 2002; Ahmed et al., 2004; Nickson et al., 2000; van Geen et al., 2003; Zheng et al., 2004). Field observations from arsenic-affected regions demonstrate a systematic progression in redox potential associated with distinct sediment color groups encountered during drilling. Although in situ redox potential (Eh) measurements may not always stabilise fully, consistent trends indicate increasingly oxidising conditions from black through white and off-white to red sediments, accompanied by characteristic shifts in groundwater chemistry (von Brömssen et al., 2007; Biswas et al., 2012a; Hossain et al., 2014).

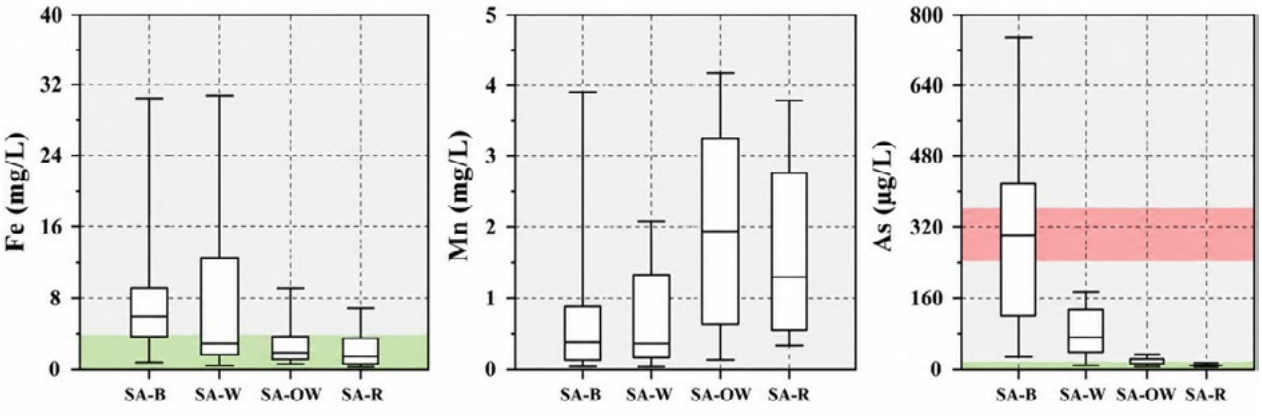


Figure 3.9: Variation in selected redox-sensitive groundwater constituents (Fe, Mn) and arsenic concentrations grouped by sediment colour class. Black sediments are associated with strongly reducing conditions and elevated arsenic, whereas progressively oxidised sediments (white, off-white, red) exhibit lower arsenic concentrations and distinct Fe–Mn behavior. The dashed line indicates the WHO guideline value for arsenic.

Groundwater abstracted from black sediments typically reflects strongly reducing conditions, with elevated concentrations of dissolved organic carbon, ammonium, iron, phosphate, and arsenic, along with low sulfate and manganese concentrations. Under these conditions, reductive dissolution of Fe(III) oxyhydr(oxides) promotes arsenic mobilisation, and elevated arsenic concentrations are common. In contrast, groundwater associated with off-white and reddish sediments generally exhibits a redox state in which manganese reduction occurs, but Fe reduction is limited, resulting in higher dissolved manganese, lower iron, and comparatively low arsenic concentrations. White sediments often represent transitional redox conditions, reflecting partial alteration of previously oxidised Fe-coated sand.

Low arsenic concentrations in more oxidised sediment units can arise either because redox conditions remain insufficiently reducing to trigger widespread dissolution of Fe(III) minerals, or because the arsenic content of the reducible sediment fraction is inherently low (Figure 3.9). However, these oxidised units may still present elevated manganese concentrations, highlighting the need to consider co-occurring redox-sensitive contaminants when identifying safe groundwater sources.

Together, these observations demonstrate that sediment colour provides a practical field proxy for redox status and groundwater composition, linking subsurface geochemistry to metal occurrence (Figure 3.10). When interpreted within a hydrostratigraphic framework, this hydrogeochemical understanding underpins source-based mitigation strategies, supports targeted aquifer selection, and complements treatment-based approaches under conditions of increasing climatic and anthropogenic stress.

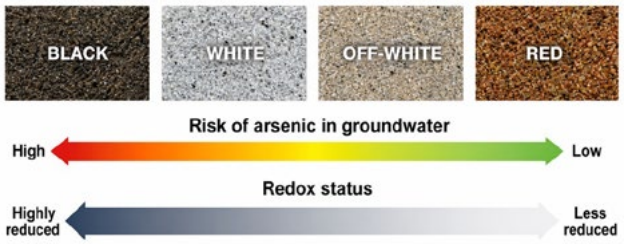


Figure 3.10: Conceptual synthesis of the relationship between sediment color, redox conditions, and arsenic risk in alluvial aquifers. Dark, reduced sediments (black) are associated with strongly reducing conditions and a high arsenic risk, whereas progressively lighter, oxidised sediments (white, off-white, red) reflect higher redox potentials and a lower likelihood of arsenic mobilisation (after von Brömssen et al., 2008).

From single-parameter compliance to system-level risk management

Conventional drinking-water management has largely relied on parameter-by-parameter compliance, where individual contaminants are assessed against fixed guideline values at the point of supply. While this approach has been effective in identifying acute risks, it is increasingly inadequate for managing groundwater systems affected by multiple co-occurring metals, temporal variability, and climate-driven change. Evidence from arsenic-affected regions demonstrates that compliance-based testing may obscure cumulative and interacting risks, particularly where mitigation strategies targeting one contaminant unintentionally increase exposure to others.

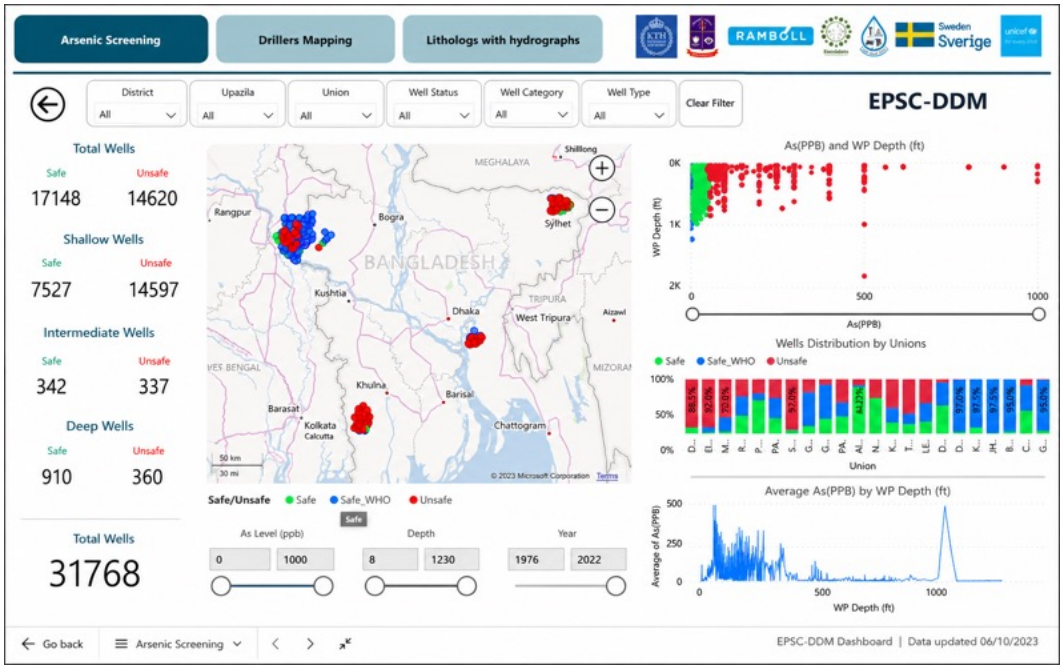


Figure 3.11: Digital groundwater monitoring and decision-support dashboard integrating arsenic screening results, well construction data, spatial distribution, and temporal trends. By consolidating field and laboratory information into a structured, decision-ready data platform, such systems support risk-based planning, enhance transparency, and strengthen multi-level groundwater governance.

A recurring challenge in groundwater systems is the co-occurrence of redox-sensitive constituents, most notably arsenic and manganese, which respond differently across redox gradients and aquifer depths. Measures such as well switching or deeper abstraction implemented to reduce arsenic exposure may result in elevated manganese concentrations, with implications for neurological and developmental health. These trade-offs highlight the limitations of single-parameter thresholds and reinforce the need for integrated exposure assessment that considers combined health risks, vulnerable populations, and long-term trends.

Recent regional-scale studies from East Africa further underscore this complexity, demonstrating widespread co-occurrence of arsenic and fluoride governed by lithological, weathering, and redox controls (Ligate et al., 2026; Mukherjee et al., 2024). Strong spatial clustering and variability in exceedances reveal that static compliance testing fails to capture evolving risk patterns. Such findings support a shift toward adaptive, system-level risk assessment, where groundwater chemistry is interpreted within its hydrogeological and climatic context.

In response, water management paradigms are increasingly moving toward preventive, system-oriented approaches, exemplified by water safety plans (WSPs). Rather than focusing solely on end-point compliance, WSPs emphasise identification of hazards from source to consumer, assessment of exposure pathways, and implementation of control measures that remain effective under variable hydrogeochemical and climatic conditions. In groundwater-dependent systems, this requires integration of hydrogeological characterisation, redox-sensitive monitoring design, and targeted mitigation strategies.

Effective system-level risk management also depends on institutional capacity and governance. Long-term monitoring programmes, coordinated data management, and transparent decision-support frameworks are essential for capturing temporal variability, detecting emerging risks, and supporting evidence-based planning. As climate change alters recharge regimes, abstraction patterns, and subsurface redox conditions, such integrated frameworks become critical for safeguarding drinking-water quality over decadal timescales.

Overall, the transition from compliance-driven monitoring to preventive, system-level risk management represents a fundamental shift in addressing metals and related substances in drinking-water systems. This shift provides the conceptual foundation for the source-based mitigation strategies, treatment optimisation, and governance approaches discussed in subsequent sections.

Field-operable science and digitalisation

Validated field tools, such as sediment-colour–based aquifer targeting, are enabling scalable implementation of groundwater risk management when combined with structured monitoring networks and digital data platforms (Figure 3.11). Digital decision-support systems reduce data loss, enhance transparency, and support evidence-based planning across local and national institutions.

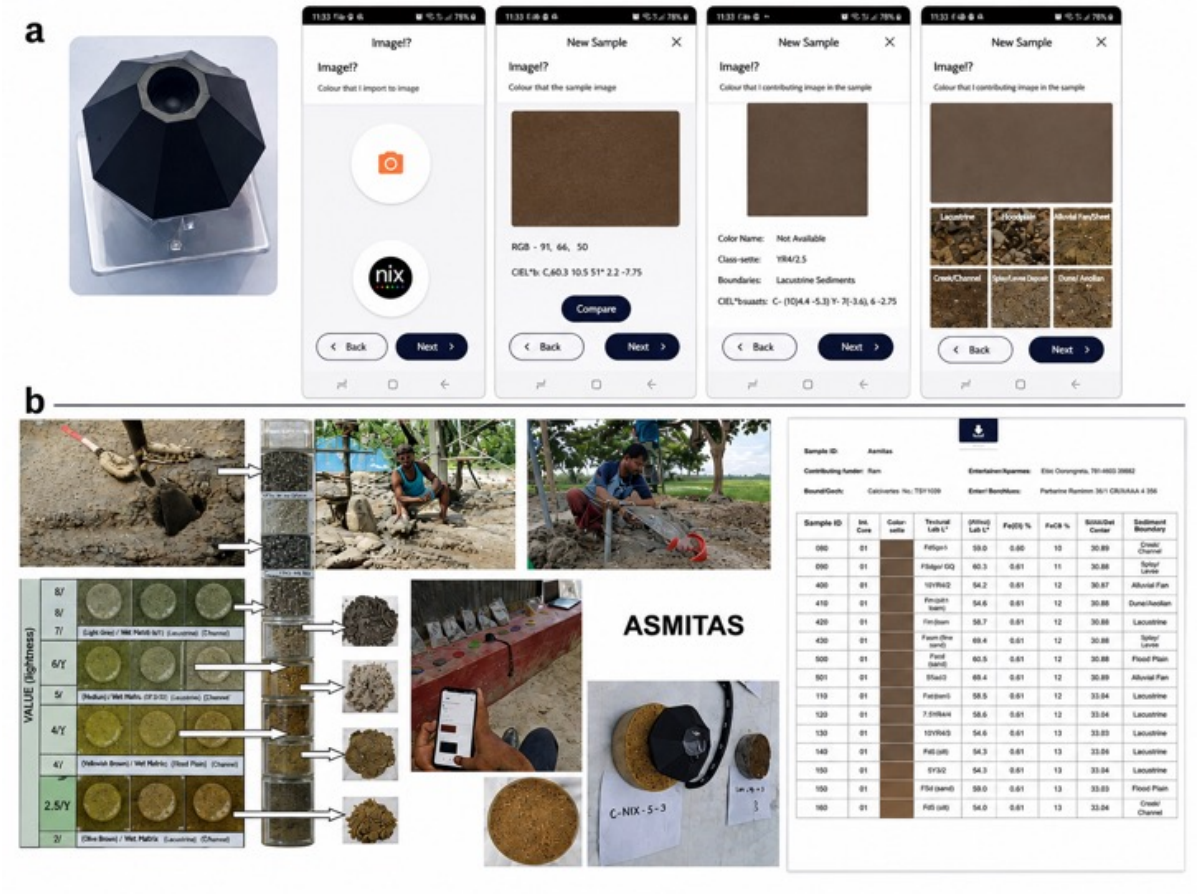


Figure 3.12: Field-operable science and digitalisation in groundwater risk management. (A) Example of mobile, field-based capture and standardisation of sediment color during drilling. (B) Integrated field-to-digital workflow illustrating sediment recovery, color classification, mobile data capture, and structured bore log generation. Together, these approaches reduce subjectivity in field interpretation, improve data traceability, and enable scalable integration of local observations into digital decision-support and water safety plan frameworks.

Translating hydrogeochemical understanding into meaningful improvements in drinking-water safety requires field-operable approaches that are scientifically robust, locally applicable, and institutionally scalable. In arsenic-affected groundwater systems, proxy-based tools, particularly sediment colour interpreted within a hydrostratigraphic framework, have demonstrated that complex subsurface processes can be operationalised through simple, low-cost decision aids. These approaches are especially effective in rural and peri-urban contexts, where local drillers rather than central utilities predominantly undertake well construction.

Field-operable science becomes transformative when embedded within systematic monitoring and digital data infrastructures. Standardised borehole logging, sediment characterisation, and groundwater-quality monitoring enable coherent spatial analysis of aquifer conditions and detection of temporal trends. Digital capture of these data reduces reliance on fragmented paper records, improves traceability, and supports consistent application of risk-based decision criteria.

Recent advances show that digital decision-support systems can integrate field observations, laboratory analyses, and sensor-based monitoring into centralised platforms accessible across institutional levels (Sharma et al., 2019; Akter et al., 2023). Mobile applications for drilling records and sediment classification, automated data validation, and interactive dashboards enable near-real-time synthesis of hydrogeological information. An example of such field-to-digital integration is shown in Figure 3.12, where sediment colour is captured and standardised during drilling using a mobile application, enabling consistent documentation and direct linkage to decision-support workflows. Such systems support adaptive management in the face of climate variability, facilitate coordination among agencies, and strengthen accountability in groundwater governance.

Importantly, digitalisation enhances, rather than replaces, local capacity and knowledge. Training and certification of drillers, coupled with digital documentation of drilling activities, transform experiential field expertise into structured datasets that inform national planning. When embedded within WSP frameworks and national mitigation strategies, the integration of field-operable science and digital platforms provides a critical bridge between research, implementation, and long-term risk reduction in groundwater-dependent drinking-water systems.

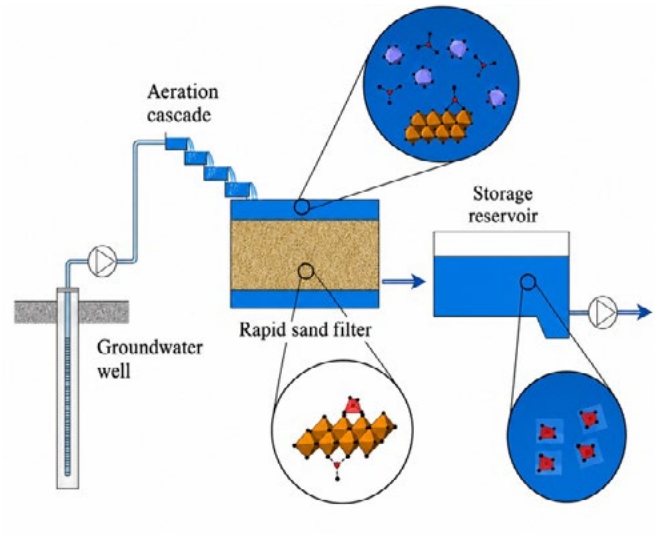
Engineered iron-based co-precipitation for arsenic removal by AOCF

Iron-based co-precipitation is a well-established mechanism for removing arsenic from drinking water and forms the basis of many groundwater treatment systems (Ahmad and Bhattacharya, 2017; Hao et al., 2018). In conventional practice, Fe(III) is generated or added to water, leading to the formation of Fe(III)-oxyhydroxides onto which arsenic is adsorbed and subsequently removed by rapid sand filtration or comparable filtration steps (Ahmad et al., 2017). Historically, this removal occurred largely as an incidental benefit of aeration and filtration rather than as a deliberately engineered process.

A key advance in arsenic mitigation has been the development of advanced oxidation, coagulation, and filtration (AOCF), in which these conventional processes are optimised by design. Research conducted during 2019–2020 demonstrated that controlling oxidation pathways, iron dosing, and filtration conditions can substantially enhance arsenic co-precipitation under full-scale operating conditions. Full-scale applications in Dutch groundwater-based drinking-water treatment facilities showed that engineered AOCF systems (Figure 3.13) can consistently reduce arsenic concentrations to below 1 µg/L, achieving significant health risk reduction with favorable cost–benefit performance (Ahmad et al., 2020a).

The effectiveness of AOCF is strongly influenced by water chemistry. Mechanistic studies have shown that phosphate, silicate, and natural organic matter affect the size, structure, and surface properties of Fe(III) precipitates and compete with arsenate for adsorption sites, thereby controlling arsenic removal efficiency (Ahmad et al., 2020b). These findings underline the need for water-matrix-specific optimisation when implementing iron-based treatment strategies.

Importantly, AOCF has moved beyond research and pilot studies and is currently implemented in Dutch drinking-water treatment facilities, integrated within existing groundwater treatment infrastructure. By enhancing conventional treatment rather than replacing it, AOCF avoids energy-intensive membrane processes and complex chemical treatment trains. As such, AOCF represents a robust, scalable, and climate-resilient treatment innovation for managing arsenic and other redox-sensitive metal(loid)s in drinking-water systems.



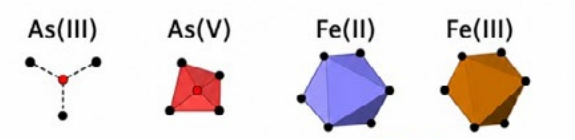


Figure 3.13: Conceptual illustration of arsenic and iron transformations during conventional groundwater treatment, showing oxidation, co-precipitation, and removal processes. As(III) is progressively oxidised to As(V), and rapid sand filtration plays a key role in determining the speciation and removal efficiency of arsenic in the treated water. Adapted from Ahmad et al. (2020a).

Case study: Bangladesh: source-based mitigation and monitoring at scale

Bangladesh is among the most comprehensively studied and operationally advanced contexts for managing geogenic arsenic in drinking water. Long-term mitigation efforts demonstrate how hydrogeological understanding, when translated into field-operable decision tools and institutional frameworks, can substantially reduce population exposure in groundwater-dependent rural settings (Hossain et al. 2017; Ahmed et al. 2019; Akter et al., 2023).

Early investigations established that arsenic occurrence in the Bengal Basin is primarily controlled by sedimentary facies, redox conditions, and aquifer lithology rather than depth alone (Nickson et al., 2000; van Geen et al., 2003; Ahmed et al., 2004; Biswas et al., 2012b). Subsequent studies showed that arsenic concentrations vary markedly over short spatial scales and can exhibit temporal variability linked to pumping intensity, recharge dynamics, and redox evolution. These findings challenged the previously simplified “shallow unsafe–deep safe” narratives and highlighted the need for context-specific aquifer targeting combined with sustained monitoring (Bhattacharya et al., 2011; Hossain et al., 2014).

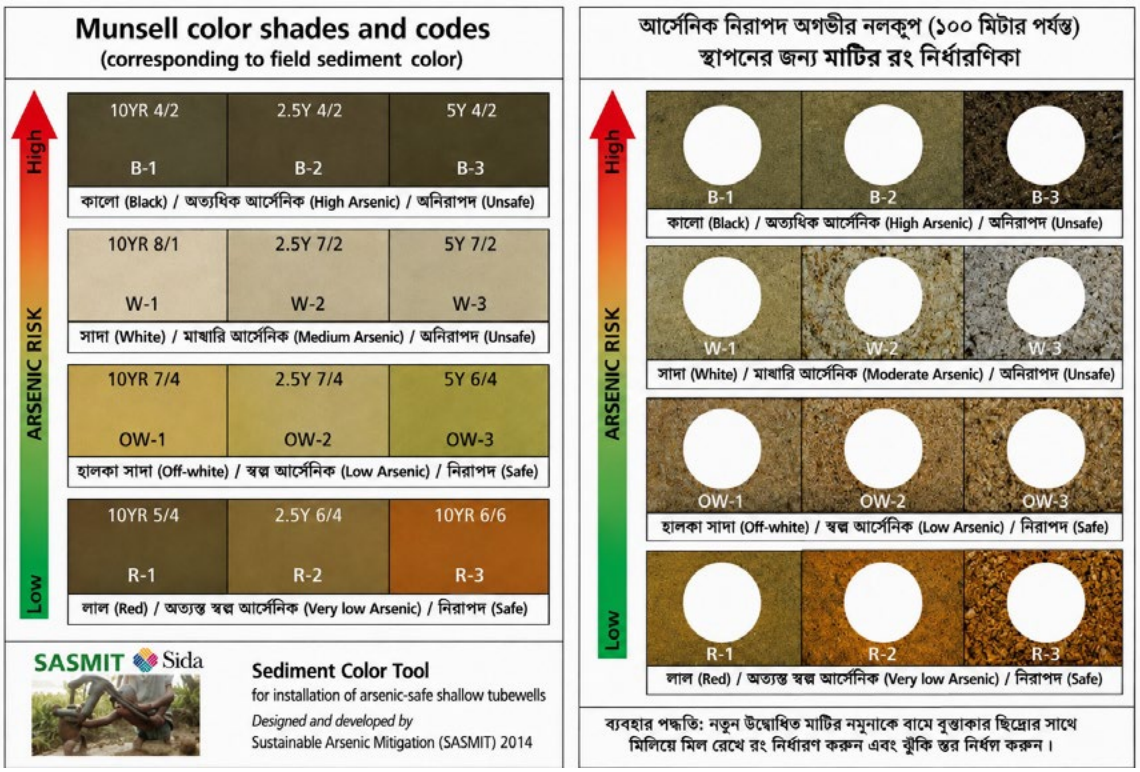


Figure 3.14: Sediment colour tool (SCT) developed for field deployment during shallow tubewell installation. The tool integrates Munsell-based sediment colour shades and codes with calibrated arsenic risk categories (high to very low). The left panel presents the standardised colour reference chart corresponding to field-observed sediment colours. The right panel shows the field-use template with circular comparison windows designed to help local drillers and stakeholders visually match freshly extracted sediments to risk classes. The tool provides a rapid, low-cost screening approach to support arsenic-safe well installation.

Shallow aquifers: sediment colour as a preventive decision tool

A major innovation emerging from this body of work is the sediment colour tool, which links observable sediment colour classes to arsenic risk within a hydrostratigraphic framework. Using standardised classification (Munsell Colour Chart), approximately 60 observed colour varieties were consolidated into four operational categories – black, white, off-white, and red sediments (Figure 3.14), suitable for application during drilling (SASMIT, 2014; Hossain et al., 2014).

Validation against Bangladesh drinking-water standards demonstrated that black sediments posed the highest arsenic risk, with average concentrations around 239 µg/L and only ~17% compliance, whereas red sediments showed 100% compliance (mean ~9.4 µg/L) and off-white sediments ~88% compliance (mean ~12.1 µg/L). Diagnostic performance metrics showed true-negative rates of approximately 83–91% for black sediments and true-positive rates up to 100% for red sediments, confirming sediment colour as a conservative and operationally robust screening proxy (Hossain et al., 2014).

Hydrochemical signatures explain these relationships. Black sediments are associated with strongly reducing conditions, elevated bicarbonate, dissolved organic carbon, Fe^{2+}, and NH_4^+, and depleted SO_4^{2-}, consistent with reductive dissolution of iron oxides and arsenic mobilisation. In contrast, red sediments reflect more oxidised depositional environments, limiting arsenic release. Off-white sediments reflect transitional redox conditions, accounting for their intermediate but generally favorable compliance (Hossain et al., 2014).

The sediment colour tool has particular significance because approximately 90% of rural tubewells in Bangladesh are installed by communities using local drillers, typically through hand-percussion drilling, the most common and cost-effective method. By enabling drillers to visually identify and avoid high-risk sediment zones during installation, the tool directly prevents unsafe wells at the point of construction, without reliance on laboratory analysis or specialised equipment. Importantly, sediment colour is a decision-support proxy, not a standalone determinant, and must be interpreted alongside aquifer continuity, clay-layer protection, and depth relationships (Hossain et al., 2017).

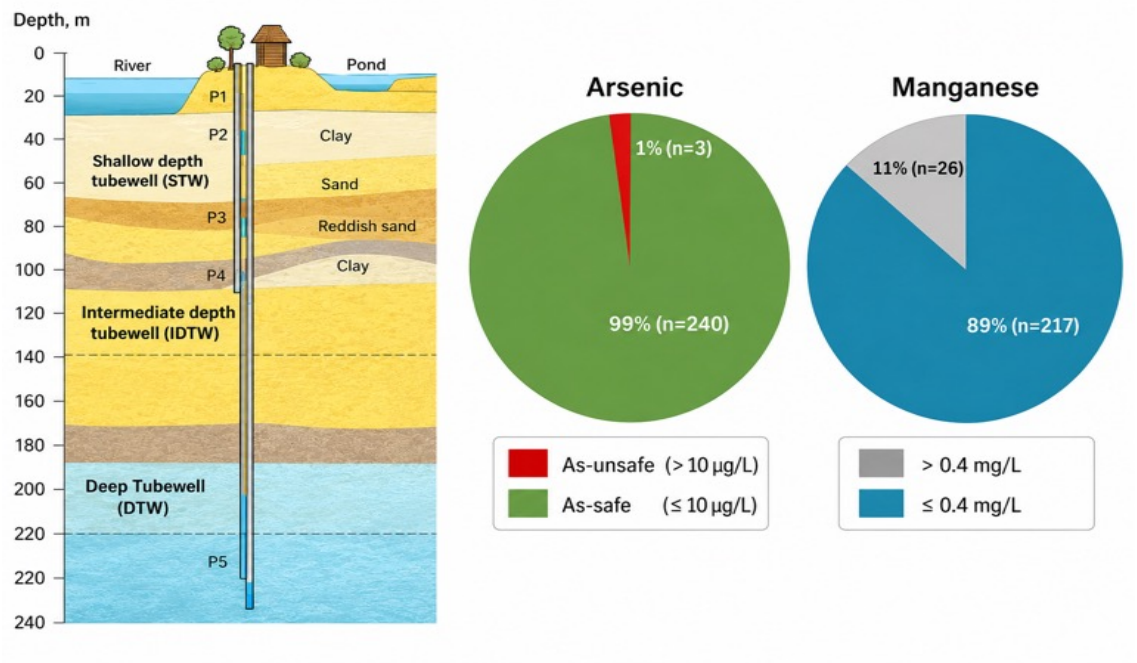


Figure 3.15: Conceptual hydrostratigraphic profile of shallow (STW), intermediate-depth (IDTW), and deep tubewells (DTW) showing sediment layers and well screen positions (left), together with the distribution of arsenic (As) and manganese (Mn) concentrations in groundwater samples (right). (Modified from Hossain et al., 2023). Arsenic concentrations are predominantly within the WHO guideline value of 10 µg/L (99% safe; n = 240), with only 1% exceeding the limit. For manganese, 89% of samples are ≤ 0.4 mg/L (n = 217), while 11% exceed 0.4 mg/L (n = 26). The figure highlights the vertical hydrostratigraphic context of groundwater abstraction and the relative prevalence of As and Mn exceedances.

Intermediate deep aquifers: low-manganese, arsenic-safe groundwater

While sediment-guided targeting has substantially improved access to safe water in shallow aquifer zones, recent work has identified intermediate deep aquifers (IDA) as a strategically important additional source of arsenic- and manganese-safe drinking water in Bangladesh (SASMIT, 2014; Hossain et al., 2023). IDAs occur between shallow Holocene aquifers and very deep Pleistocene systems (Figure 3.15) and represent a previously underutilised, but highly promising resource.

Hydrochemical evidence shows that IDA groundwaters are characterised by conditions unfavourable for arsenic mobilisation, including moderate redox potentials (mean Eh ≈ 154 mV), low dissolved organic carbon (~2.6 mg/L), and moderate bicarbonate concentrations (~203 mg/L). These conditions limit reductive dissolution of iron oxides, the dominant mechanism releasing arsenic in shallow aquifers. As a result, IDA waters exhibit consistently low arsenic concentrations (mean ~6.2 µg/L; median ~3.9 µg/L), well below the WHO guideline value (Hossain et al., 2023).

Importantly, IDAs also show low manganese concentrations, addressing an increasingly recognised co-risk in arsenic mitigation programmes where switching sources can inadvertently increase Mn exposure. Trace elements such as Cd, Co, Cr, Mo, Ni, and Pb are generally present at very low levels, indicating broad chemical suitability for drinking-water supply (Hossain et al., 2023).

From an implementation perspective, IDAs offer a balanced compromise between shallow aquifer targeting and very deep abstraction. They can often be accessed at moderate depths using locally available drilling techniques and at approximately half the cost of deep tubewells, making them financially accessible for community-driven installations. When combined with sediment colour logging and hydrostratigraphic interpretation, IDA targeting significantly expands the portfolio of source-based mitigation options while reducing reliance on treatment-based solutions.

Monitoring, governance, and scaling

Long-term hydrogeochemical investigations in Bangladesh have demonstrated that arsenic concentrations in individual wells are not static. Seasonal recharge, abstraction intensity, redox evolution, and hydraulic connectivity can induce measurable temporal variability in groundwater composition. These findings exposed the limitations of one-off blanket screening campaigns, which, while essential for rapid risk identification, are insufficient for long-term protection of drinking-water safety. Repeated sampling in monitoring wells revealed vertical and temporal heterogeneity within aquifer sequences, underscoring the importance of integrating lithological logging, sediment colour classification, and hydraulic understanding into monitoring design (Hossain et al., 2017).

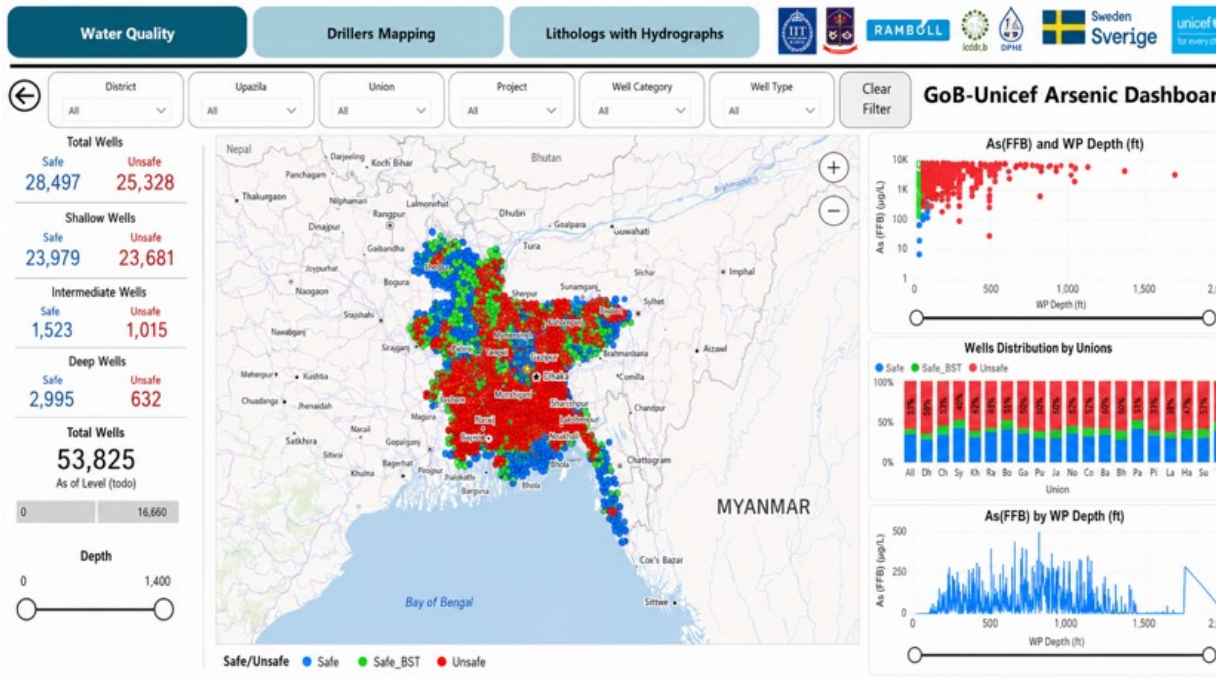


Figure 3.16: National digital dashboard integrating arsenic screening results, well depth, and spatial distribution across Bangladesh. The platform aggregates field and laboratory data into a structured, decision-support system that enables spatial risk assessment, trend analysis, and coordinated groundwater governance at scale.

In response, structured multi-level monitoring networks were developed to capture vertical redox gradients and evolving contaminant distributions. Such networks explicitly link water-quality trends to stratigraphy and groundwater flow conditions, enabling differentiation among shallow Holocene reducing units, intermediate aquifers, and deeper oxidised sands. This approach marked a shift from reactive testing toward predictive, hydrogeologically informed surveillance.

The Government of Bangladesh–UNICEF WASH Project (2022) represents a significant step in institutionalising these lessons at the national scale. The guidelines formalise procedures for monitoring-well siting, standardised lithological and sediment-colour logging, quality assurance protocols, and digital data management (Figure 3.16). By embedding hydrogeochemical reasoning within administrative procedures, the framework moves beyond project-based interventions toward coordinated groundwater governance. Digital documentation of bore-logs and monitoring results strengthens traceability, reduces data fragmentation, and enables cross-agency data sharing – critical elements for sustained risk management.

Scaling arsenic mitigation, therefore, required more than identifying safe aquifers; it required integration of science, institutions, and data systems. Preventive source selection, structured monitoring, and digital record-keeping together create a feedback loop in which field observations inform national planning, and national strategies guide local implementation. As climate variability and abstraction pressures evolve, such institutionalised monitoring frameworks provide resilience by enabling adaptive responses rather than periodic crisis-driven interventions.

Key lessons learned

1. **Preventive source-based mitigation** can reduce arsenic exposure more rapidly and sustainably than post-hoc treatment alone.
2. **Sediment colour tools,** when embedded within hydrostratigraphic interpretation, enable immediate, low-cost risk reduction at the point of well installation.
3. **Intermediate deep aquifers (IDA)** expand the portfolio of safe supply options, particularly where manganese co-occurrence complicates shallow mitigation strategies.
4. **Long-term, multi-level monitoring** is essential to capture temporal and vertical variability and to avoid complacency following initial screening.
5. **Institutionalisation and digitalisation** – including standardised logging, quality assurance, and shared databases – are critical for scaling mitigation and ensuring climate-resilient groundwater governance.

Together, these elements illustrate Bangladesh's transition from emergency arsenic response toward a *preventive, system-oriented drinking-water safety model*. The experience demonstrates how hydrogeological science, when embedded within governance structures and digital monitoring systems, can transform a large-scale geogenic contamination crisis into a managed, adaptive public-health strategy. This model offers transferable lessons for managing metals and related substances in groundwater-dependent regions worldwide.

Recommendations

Policy and governance

- **Institutionalise risk-based drinking-water safety management** that explicitly integrates hydrogeological characterisation, structured monitoring networks, and public-health surveillance within national water safety plan frameworks.
- **Move beyond single-parameter compliance models** by incorporating multi-contaminant risk assessment, cumulative exposure considerations, and temporal variability into regulatory standards and reporting systems.
- **Mandate standardised borelog documentation and digital data archiving** to ensure traceability, transparency, and long-term continuity of groundwater quality information.
- **Embed climate resilience into groundwater governance**, recognising that recharge variability, abstraction pressures, and redox evolution can alter contaminant mobility over time.

Utilities and implementation

- **Prioritise preventive, source-based mitigation strategies**, including sediment-informed aquifer targeting and intermediate-depth resource development, before reliance on treatment technologies.
- **Deploy validated field-operable tools** at the point of well installation to reduce exposure risks immediately and cost-effectively.
- Where source substitution alone is insufficient, **apply optimised AOCF** or comparable iron-based processes under robust operational control and water-matrix–specific optimisation.
- Establish **routine, adaptive monitoring protocols** capable of detecting vertical and temporal variability in groundwater quality.

Research and innovation

- Advance **climate-sensitive hydrogeochemical research** to better understand long-term contaminant mobilisation, redox evolution, and aquifer resilience.
- Expand **integrated digital decision-support systems** that connect field observations, laboratory data, and governance frameworks into structured, interoperable data platforms.
- Strengthen interdisciplinary research linking **hydrogeochemistry, exposure science, and public health outcomes**, particularly in multi-contaminant groundwater systems.
- Promote innovation in **low-energy, iron-based treatment optimisation**, especially for complex water matrices where competing solutes affect removal efficiency.

Taken together, the evidence presented in this chapter demonstrates that managing metals and related substances in groundwater requires a shift from reactive compliance toward preventive, system-oriented risk governance. Integrating hydrogeochemical understanding, field-operable tools, optimised treatment technologies, and structured digital monitoring systems creates a coherent pathway from science to sustained public-health protection. As climate variability and abstraction pressures intensify, countries that embed these principles within institutional frameworks will be better positioned to safeguard drinking-water quality over the coming decades.

Conclusions

Metals and related inorganic substances in drinking water remain a persistent and evolving challenge shaped by complex hydrogeochemical processes, cumulative exposure risks, and increasing climatic variability. Evidence from diverse groundwater systems demonstrates that contaminant occurrence is governed by interacting redox, lithological, and hydrological controls that cannot be managed through isolated parameter-based compliance alone.

Sustained progress requires a transition toward preventive, system-level risk management, integrating hydrogeological characterisation, structured monitoring networks, validated field-operable tools, digital decision-support systems, and optimised treatment technologies such as Advanced Oxidation, Coagulation, and Filtration (AOCF). When embedded within institutional governance frameworks and water safety plan approaches, these elements create a coherent pathway from scientific understanding to long-term public-health protection.

As abstraction pressures intensify and climate change alters groundwater dynamics, the need for integrated and adaptive management will become even more critical. Through its interdisciplinary expertise spanning geochemistry, engineering, monitoring, and governance, METRELS is well positioned to provide global leadership in advancing resilient, evidence-based strategies for safeguarding drinking-water quality in groundwater-dependent regions worldwide.

References

Agency for Toxic Substances and Disease Registry (ATSDR). (2020). Toxicological profile for lead. U.S. Department of Health and Human Services, Public Health Service.

Agency for Toxic Substances and Disease Registry (ATSDR). (2022). Toxicological profile for copper. U.S. Department of Health and Human Services, Public Health Service.

Ahmad, A., & Bhattacharya, P. (2017). Tackling the king of poisons: Source substitution and treatment can help tackle naturally occurring arsenic. *The Source*, October 2017, 57–58.

Ahmad, A., Richards, L. A., & Bhattacharya, P. (2017). Arsenic remediation of drinking water: An overview. In P. Bhattacharya, D. A. Polya, & D. Jovanovic (Eds.), *Best Practice Guide on the Control of Arsenic in Drinking Water* (pp. 79–98). IWA Publishing. https://doi.org/10.2166/9781780404929_079

Ahmad, A., Van Dijk, T., Gude, J., van de Wetering, S., Groenendijk, M., & Bhattacharya, P. (2017). Remediation case study: Drinking water treatment by AOCF to target <1 µg L−1 effluent arsenic concentration. In P. Bhattacharya, D. A. Polya, & D. Jovanovic (Eds.), *Best Practice Guide on the Control of Arsenic in Drinking Water* (pp. 219–225). IWA Publishing. https://doi.org/10.2166/9781780404929_219

Ahmad, A., van der Wens, P., Baken, K., de Waal, L., Bhattacharya, P., & Stuyfzand, P. (2020a). Arsenic reduction to <1 µg/L in Dutch drinking water. *Environment International*, 134, 105253. https://doi.org/10.1016/j.envint.2019.105253

Ahmad, A., Rutten, S., Eikelboom, M., de Waal, L., Bruning, H., Bhattacharya, P., & van der Wal, A. (2020b). Impact of phosphate, silicate and natural organic matter on the size of Fe(III) precipitates and arsenate coprecipitation efficiency in calcium-containing water. *Separation and Purification Technology*, 235, 116117. https://doi.org/10.1016/j.seppur.2019.116117

Ahmed, K. M., Bhattacharya, P., Hasan, M. A., Akhter, S. H., Alam, S. M. M., Bhuyian, M. A. H., Imam, M. B., Khan, A. A., & Sracek, O. (2004). Arsenic contamination in groundwater of alluvial aquifers in Bangladesh: An overview. *Applied Geochemistry*, 19(2), 181–200. https://doi.org/10.1016/j.apgeochem.2003.09.006

Ahmed, K. M., van Geen, A., & Bhattacharya, P. (2019). Implementation of arsenic mitigation: Insights from Araihazar and Matlab—two extensively studied areas in Bangladesh. In Y. G. Zhu et al. (Eds.), *Environmental Arsenic in a Changing World As 2018* (pp. 565–566). CRC Press.

Akter, N., Johnston, D., Niang, M., Jurji, Z., Khan, E. R., Rahman, M. S., Khan, T. M. S., Islam, M. T., Ahmed, K. M., & Bhattacharya, P. (2023). System strengthening and scaling up drinking water safety for arsenic risk reduction in Bangladesh. In A. van der Wal et al. (Eds.), *Arsenic in the Environment: Bridging Science to Practice for Sustainable Development As 2021* (pp. 431–432). CRC Press.

Ali, S., Fakhri, Y., Golbini, M., Thakur, S. K., Alinejad, A., Parseh, I., Shekhar, S., & Bhattacharya, P. (2019). Concentration of fluoride in groundwater of India: A systematic review, meta-analysis and risk assessment. *Groundwater for Sustainable Development*, 9, 100224. https://doi.org/10.1016/j.gsd.2019.100224

Bhattacharya, P., Frisbie, S. H., Smith, E., Naidu, R., Jacks, G., & Sarkar, B. (2002). Arsenic in the environment: A global perspective. In B. Sarkar (Ed.), *Handbook of Heavy Metals in the Environment* (pp. 147–215). Marcel Dekker.

Bhattacharya, P., Hasan, M. A., Sracek, O., Smith, E., Ahmed, K. M., von Brömssen, M., Huq, S. M. I., & Naidu, R. (2009). Groundwater chemistry and arsenic mobilization in the Holocene flood plains in south-central Bangladesh. *Environmental Geochemistry and Health*, 31, 23–44. https://doi.org/10.1007/s10653-008-9230-5

Bhattacharya, P., Hossain, M., Rahman, S. N., Robinson, C., Nath, B., Rahman, M., Islam, M. M., von Brömssen, M., Ahmed, K. M., Jacks, G., Chowdhury, D., Jakariya, M., Persson, L.-Å., & Vahter, M. (2011). Temporal and seasonal variability of arsenic in drinking water wells in Matlab, Bangladesh. *Journal of Environmental Science & Health*, Part A, 46(11), 1177–1184. https://doi.org/10.1080/10934529.2011.598768

Biswas, A., Nath, B., Bhattacharya, P., Halder, D., Kundu, A. K., Mandal, U., Mukherjee, A., Chatterjee, D., & Jacks, G. (2012a). Testing tubewell platform color as a rapid screening tool. *Environmental Science & Technology*, 46, 434–440. https://doi.org/10.1021/es203058a

Biswas, A., Nath, B., Bhattacharya, P., Halder, D., Kundu, A. K., Mandal, U., Mukherjee, A., Chatterjee, D., Mörth, C.-M., & Jacks, G. (2012b). Hydrogeochemical contrast between aquifers. *Science of the Total Environment*, 431, 402–412. https://doi.org/10.1016/j.scitotenv.2012.05.031

Bundschuh, J., Bhattacharya, P., Hoinkis, J., Kabay, N., Jean, J.-S., & Litter, M. I. (2010). Groundwater arsenic: From genesis to remediation. *Water Research*, 44(19), 5511. https://doi.org/10.1016/j.watres.2010.10.028

Edwards, M., & Dudi, A. (2004). Role of chlorine and chloramine in corrosion. *Journal AWWA*, 96(10), 69–81. https://doi.org/10.1002/j.1551-8833.2004.tb10724.x

Edzwald, J. K. (2020). Aluminum in drinking water. *Journal AWWA*, 112(5), 34–41.

Eggleton, J., & Thomas, K. V. (2004). Contaminant release during sediment disturbance. *Environment International*, 30(7), 973–980.

Esdaile, L. J., & Chalker, J. M. (2018). Mercury problem in gold mining. *Chemistry – A European Journal,* 24(27), 6905–6916.

Government of Bangladesh & UNICEF. (2022). Location Selection and Implementation Guideline for Groundwater Monitoring Wells. Dhaka.

Hao, L., Liu, M., Wang, N., & Li, G. (2018). Arsenic removal using iron-based adsorbents. *RSC Advances*, 8, 39545–39560. https://doi.org/10.1039/c8ra08512a

Hasan, M. A., Bhattacharya, P., Sracek, O., Ahmed, K. M., von Brömssen, M., & Jacks, G. (2009). Geological controls on groundwater chemistry. *Journal of Hydrology*, 378, 105–118. https://doi.org/10.1016/j.jhydrol.2009.09.016

Hossain, M., Bhattacharya, P., Frape, S. K., Jacks, G., Islam, M. M., Rahman, M. M., Hasan, M. A., & Ahmed, K. M. (2014). Sediment color tool for arsenic-safe aquifers. *Science of the Total Environment*, 493, 615–625. https://doi.org/10.1016/j.scitotenv.2014.05.064

Hossain, M., Bhattacharya, P., Jacks, G., von Brömssen, M., Ahmed, K. M., Hasan, M. A., & Frape, S. K. (2017). Sustainable arsenic mitigation. In P. Bhattacharya et al. (Eds.), *Best Practice Guide on the Control of Arsenic in Drinking Water* (pp. 99–116). IWA Publishing. https://doi.org/10.2166/9781780404929_099

Hossain, M., Bhattacharya, P., Frape, S. K., Ahmed, K. M., Jacks, G., Hasan, M. A., von Brömssen, M., Shahiruzzaman, M., & Mörth, C.-M. (2023). Intermediate deep aquifers as safe water source. *Groundwater for Sustainable Development*, 21, 100906. https://doi.org/10.1016/j.gsd.2023.100906

Kapaj, S., Peterson, H., Liber, K., & Bhattacharya, P. (2006). Human health effects of arsenic poisoning. *Journal of Environmental Science & Health*, 41(10), 2399–2428. https://doi.org/10.1080/10934520600873571

Krupińska, I. (2020). Aluminium residuals and toxicity. *Molecules*, 25(3), 641.

Ligate, F., Ijumulana, J., Irunde, R., Kimambo, V., Hamisi, R., Maity, J. P., Mtamba, J., Mtalo, F., & Bhattacharya, P. (2026). Hydrogeochemistry in Lake Victoria Basin. *Journal of Environmental Science, Health & Sustainability*, 2(1), 30–50. https://doi.org/10.63697/jeshs.2026.10033

Macklin, M. G., Thomas, C. J., Mudbhatkal, A., Brewer, P. A., Hudson-Edwards, K. A., Lewin, J., et al. (2023). Impacts of metal mining on rivers. *Science*, 381, 1345–1350.

Miller, J. R., Hudson-Edwards, K. A., Lechler, P. J., Preston, D., & Macklin, M. G. (2004). Heavy metal contamination in Bolivia. *Science of the Total Environment*, 320, 189–209.

Mukherjee, A., Bhattacharya, P., Shi, F., Fryar, A. E., Mukherjee, A. B., Xie, Z. M., Sracek, O., Jacks, G., & Bundschuh, J. (2009). Solute chemistry evolution trends. *Applied Geochemistry*, 24, 1835–1851. https://doi.org/10.1016/j.apgeochem.2009.06.005

Mukherjee, A., Coomar, P., Sarkar, S., Ahmed, K. M., Alam, M. A., Bhattacharya, P., et al. (2024). Geogenic arsenic in groundwater. *Nature Reviews Earth & Environment*, 5, 312–328. https://doi.org/10.1038/s43017-024-00519-z

Nickson, R. T., McArthur, J. M., Ravenscroft, P., Burgess, W. G., & Ahmed, K. M. (2000). Mechanism of arsenic release. *Applied Geochemistry*, 15, 403–413.

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., et al. (2009). Toxicology of climate change. *Environment International*, 35, 971–986.

Pieper, K. J., Tang, M., & Edwards, M. A. (2017). Flint water crisis investigation. *Environmental Science & Technology*, 51, 2007–2014.

Pieper, K. J., Martin, R., Tang, M., Walters, L., Parks, J., Roy, S., et al. (2018). Water lead levels in Flint. *Environmental Science & Technology*, 52, 8124–8132.

Saha, R., Nandi, R., & Saha, B. (2011). Chromium toxicity. *Journal of Coordination Chemistry*, 64, 1782–1806.

SASMIT. (2014). Sustainable arsenic mitigation concept note. KTH Royal Institute of Technology.

Schock, M. R. (1989). Corrosion control strategies. *Journal AWWA*, 81, 88–100.

Sharma, S., Bhattacharya, P., Kumar, D., Perugupalli, P., von Brömssen, M., Islam, M. T., & Jakariya, M. (2019). *ASMITAS application*. CRC Press.

Singh, N., Jacks, G., & Bhattacharya, P. (2005). Women and water supply programs. *Natural Resources Forum*, 29, 213–223.

van Geen, A., Zheng, Y., Goodbred, S., Horneman, A., Aziz, Z., Cheng, Z., et al. (2003). Spatial variability of arsenic. *Water Resources Research*, 39, 1140.

von Brömssen, M., Jakariya, M., Bhattacharya, P., Ahmed, K. M., Hasan, M. A., Sracek, O., et al. (2007). Targeting low-arsenic aquifers. *Science of the Total Environment*, 379, 121–132.

von Brömssen, M., Larsson, S. H., Bhattacharya, P., Hasan, M. A., Ahmed, K. M., Jakariya, M., et al. (2008). Geochemical characterization of aquifers. *Journal of Contaminant Hydrology*, 99, 137–149.

WHO. (2010). Aluminium in drinking-water. World Health Organization.

WHO. (2022). Guidelines for drinking-water quality (4th ed.). World Health Organization.

Zheng, Y., Stute, M., van Geen, A., Gavrieli, I., Dhar, R., Simpson, H. J., et al. (2004). Redox control of arsenic mobilization. *Applied Geochemistry*, 19, 201–214.

Zhou, Q., Yang, N., Li, Y., Ren, B., Ding, X., Bian, H., & Yao, X. (2020). Heavy metal pollution trends. *Global Ecology and Conservation*, 22, e00925.

| 3.5 |

Global trends & challenges: health-related water microbiology

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Introduction

Health-Related Water Microbiology (HRWM) is one of the Specialist Groups of the International Water Association (IWA). It was the very first Specialist Group, established in 1977 as the Water Virology Specialist Group within the former International Association on Water Pollution Research and Control (IAWPRC). The Group serves as a forum for the exchange of scientific knowledge in the field of health-related water microbiology. Its scope spans a wide range of disciplines: from environmental to clinical virological, bacteriological, and parasitological diagnostics; from infectious disease epidemiology to risk assessment methodologies; and from water treatment engineering to environmental health practice. In this chapter, we highlight recent progress in the field of health-related water microbiology.

Key terminology

- **Water quality guidelines:** Recommended science-based thresholds for biological, chemical, and physical parameters in water bodies, designed to protect human health, aquatic ecosystems, and industrial or agricultural usage.
- **Global Water Pathogen Project:** An open-access initiative led by UNESCO and Michigan State University that serves as a global knowledge hub, providing scientific data, tools, and resources on waterborne pathogens to improve sanitation and protect public health.
- **Microbial source tracking:** A suite of scientific techniques used to identify the specific human or animal origin of fecal contamination in water systems by targeting host-associated genetic or microbial markers.
- **Antimicrobial resistance:** Microorganisms like bacteria, viruses, fungi, and parasites develop the ability to defeat the drugs designed to kill them, causing treatments to fail and allowing infections to persist and spread.
- **Wastewater reclamation and reuse:** Treating and repurposing wastewater from homes and industries turns it into a valuable resource for irrigation, industrial processes, or drinking.
- **Disaster and public health:** Protecting population health during emergencies involves preventing disease outbreaks, managing mass injuries, delivering essential care, and restoring critical medical infrastructure to minimize mortality when catastrophic events strike.

Key insights

Health-related water microbiology is advancing rapidly across risk assessment, microbial source tracking (MST), antimicrobial resistance (AMR), wastewater reuse, and disaster resilience. Quantitative microbial risk assessment (QMRA) frameworks and the Global Water Pathogen Project (GWPP) are shaping risk-based guidelines and global knowledge platforms. MST is evolving from single-marker assays to metagenomic and community-based approaches, integrating with QMRA for actionable health risk metrics. AMR research highlights wastewater systems as resistance hotspots, driving innovation in monitoring, predictive modelling, and advanced treatment. Wastewater reuse emphasises multi-barrier safety, AI-driven optimisation, and management of emerging contaminants. Disaster-focused studies reveal how extreme events disrupt microbial water quality, prompting rapid detection, and resilience strategies.

Case study

Risk assessment and guideline development, and Global Water Pathogen Project

Some of main SG members have devoted to the development of quantitative microbial risk assessment (QMRA) framework for many years. Their sustained efforts to establish and apply the QMRA framework have contributed significantly to the development of risk-based water quality guidelines and standards for microbial water quality. Over time, experts from the group have also participated in WHO working groups to draft and revise these guidelines.

Guidelines are frequently updated to reflect the latest scientific knowledge on newly identified and emerging pathogens, improved treatment technologies, and advanced detection methods. Increasingly, guideline development is adopting a risk-based approach that incorporates electronic decision support systems to aid in decision-making.

One of the leading projects in this area is the Global Water Pathogen Project (GWPP). The GWPP publication Water and Sanitation for the 21st Century: Health and Microbiological Aspects of Excreta and Wastewater Management' was realised by the Intergovernmental Hydrological Programme (IHP) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO), in collaboration with Michigan State University (MSU) and many supporting leading scientists in their specific fields. The GWPP provides a comprehensive knowledge resource to reduce mortality associated with waterborne pathogens and the lack of safe drinking water and basic sanitation. It is the most comprehensive state-of-the-art knowledge hub on water-related disease risks and intervention measures, incorporating information on new and emerging pathogens, and providing updated scientific data to replace the long-standing benchmark. The content is accessible through an online database and knowledge platform, ensuring broad international availability and continuous updates via a global higher education network (https://www.waterpathogens.org/).

The knowledge generated through this project will also be published as a UNESCO book in English, French, and Spanish very soon. In addition, the GWPP editorial board has started activities to establish a second GWPP edition (scheduled for 2030).

Recent activities in the evaluation and application of microbial source tracking marker

Microbial source tracking (MST) refers to a suite of methods aiming to identify the origins (e.g. human, livestock, wildlife, birds) of fecal contamination in water bodies. While classical approaches used indicator bacteria that could not distinguish sources, recent advances increasingly leverage molecular, community-based, and integrative methods to enhance resolution, robustness, and risk assessment linkage (Demeter et al., 2023). The field of molecular detection of markers and genes to characterise fecal pollution in water and water resources has recently been defined as genetic fecal pollution diagnostics (GFPD) (Demeter et al., 2023).

Genetic marker-based MST: refinement and new host markers

Genetic marker-based MST (often qPCR or digital PCR assays targeting host-associated bacteria, viruses, or mitochondrial DNA) remains a core approach. For example, widely used human-associated *Bacteroides* markers (like HF183) continue to be refined for fecal specificity and sensitivity as well as persistence under environmental stresses (Corbeil et al., 2025). Recent work from Ruti et al. (2025) evaluated both bovine mtDNA and CrAssphage markers in river water, reporting detection rates of ~38% and ~67% respectively, emphasising the utility and challenges of applying multiple MST markers in real systems. A recent study by Murphy et al. (2025) examined how non-methodological (e.g. seasonality, environmental conditions) and methodological factors influence the probability of detecting host-specific MST markers in surface waters. They found that both method choice and seasonal variation strongly affect detection rates. This highlights that MST interpretation must carefully consider ecological and temporal variability. Besides fecal sensitivity, specificity, and persistence there is also a lack of knowledge on the mobility of genetic markers in wastewater treatment (e.g. water vs sludge fraction), surface water (e.g. particle attachment behavior), and groundwater (Detemer et al., 2023).

Microbiome / community-based MST and "next-generation" approaches

To extend single-marker methods, there is a strong trend toward leveraging microbial community fingerprinting and metagenomic or amplicon sequencing for MST. These approaches consider the overall microbial composition of known source libraries and compare them to environmental "sink" communities (Paruch and Paruch, 2024). Tools like SourceTracker2 use Bayesian models to apportion source

contributions based on community signatures (Unno et al., 2018). However, most of these applications still remains applied only at highly fecal polluted water resources, as the quantitative fecal sensitivity of these sequencing-based MST strategies (i.e. sample limit of detection) is currently very limited (Detemer et al., 2023)

Integration with quantitative risk assessment

A major recent advance is to combine MST data with QMRA to estimate human health risk associated with exposure to fecal contamination from specific sources (Detemer et al., 2023). For instance, a study in Iowa, USA, applied 36 qPCR assays (pathogens + multiple source markers) across six river sites, and estimated acute gastrointestinal illness risk by apportioning contributions from human, livestock, and wildlife sources (Burch et al., 2024). One key finding was that multiple simultaneous fecal sources, rather than a single dominant source, often drive "high-risk" exposures. Such integrative work helps translate MST outputs into actionable risk metrics for water managers. In addition, genetic MST marker can be used to specifically calibrate and verify catchment-based QMRA models (e.g. QMRAcatch) in order to realise scenario modelling, such as to establish climate- and global resilient pathogen log reduction targets for drinking water production from river catchments (Derx et al., 2021; Detemer et al., 2021)

Performance, quality control and standardisation

As MST techniques proliferate, there is increasing focus on performance validation, quality assurance, inter-laboratory comparability, and decay dynamics of markers. The review "Current status of microbial source tracking applications" (Paruch and Paruch, 2024) discusses real-world MST deployments, challenges in marker performance under variable environments, and the need for standard protocols for sampling, assay thresholds, and data interpretation. Likewise, Unno et al. (2018) reviews advances in next-gen MST, particularly how metagenomics and bioinformatics are reshaping MST but also raising challenges about data complexity and transferability. Finally, in a review by Demeter et al (2023), the whole area of genetic fecal pollution diagnostics of water – including MST as the dominating scientific application – is analysed from the very beginning, i.e. about three decades ago (Detemer et al., 2023)

Applications and case studies

Recent case studies demonstrate MST in action for water quality management. For example, in Texas, a coastal recreational water study used HF183 and *Enterococcus* assays to disentangle human vs avian contributions during times of high fecal indicator bacteria (FIB) (Sefcik et al., 2025). They found strong signals of avian source dominance but also detected human-associated *Enterococcus* in some samples, revealing complexity in source contributions.

Antimicrobial resistance in the water environment

Antimicrobial resistance in water environments has gained increasing attention as a critical dimension of the global AMR crisis. Water bodies act both as reservoirs and transmission pathways for antibiotic-resistant bacteria (ARB), antibiotic resistance genes (ARGs), and residual antimicrobials. Recent studies have advanced our understanding of key drivers, spatial-temporal dynamics, and mitigation strategies.

Key trends and findings

Municipal wastewater treatment plants (WWTPs) remain central foci: they receive loads of antibiotics, ARB, and ARGs from households, hospitals, agriculture, and industries. WWTPs thus act as "hotspots" for resistance mobilisation and dissemination (Talat et al., 2025). Recent scoping reviews emphasise how effluents, hospital wastewater, and urban discharges contribute to the environmental AMR burden (Lan et al., 2025). Studies comparing treatment methods (chlorination, UV, advanced oxidation) highlight that conventional processes may reduce but not eliminate ARGs/ARB, prompting interest in advanced methods (Calero-Caceres, 2024).

ARGS AND RESISTOME PROFILING ACROSS WATER TYPES

The diversity, abundance, and persistence of ARGs across river, lake, groundwater, and coastal systems are being mapped more intensively. A particularly recent study in profiles the "resistome risk" across diverse water environments, linking ARG diversity to environmental and anthropogenic pressures (Yang et al., 2025). Riverine studies show that ARG abundance and persistence correlate with factors like nutrient load, hydrology, microbial community structure, and fecal pollution (Naznine et al., 2025). In a case from Bangladesh, multi-resistant enteric bacteria (e.g. *E. coli, Salmonella, Vibrio*) were found across various water sources, with genotypes (e.g. bla_TEM, qnrB, sul1, tetA) similar to clinical isolates, emphasising cross-ecosystem connectivity (Dey et al., 2025).

CLIMATE AND ENVIRONMENTAL DRIVERS

Recent reviews examine how rising water temperature and climate change influence resistance evolution. Warmer surface waters can foster faster bacterial growth, increase mutation rates, and reduce fitness costs of resistance (Zhao et al., 2024). Moreover, climate-driven hydrological changes (e.g. more runoff, flooding) may increase dissemination of ARGs from

soils or sewage into water bodies (Ouyang et al., 2024). Also, heavy metals and co-selective agents in water can promote ARG selection even in absence of antibiotics (Calero-Caceres, 2024).

ADVANCEMENTS IN METHODOLOGY AND MONITORING FRAMEWORKS

Metagenomics, resistome risk scoring, and machine learning approaches are being increasingly used to characterise complex ARG datasets and prioritise high-risk genes (Yang et al., 2025). Efforts toward standardisation of AMR monitoring in aquatic systems are rising. A reference framework for monitoring wastewater, recycled water, and surface water seeks to harmonise sampling, quantification, and reporting (Calero-Caceres, 2024). Novel methods, such as explainable AI, are being applied to dissect which environmental variables most influence ARG prevalence (Monaco et al., 2025).

INTERVENTION STRATEGIES AND REMOVAL TECHNOLOGIES

To reduce AMR in water, advanced treatment methods are gaining momentum. These include advanced oxidation processes (AOPs), electrochemical oxidation, membrane-based separation, and combined hybrid systems (Calero-Caceres, 2024). Risk assessment efforts are also evolving: e.g. a Water Research Foundation (WaterRF) project created a science-grounded AMR risk assessment framework for water systems for utility application (The Water Research Foundation, 2024).

Wastewater reclamation and reuse

In response to increasing water scarcity, population growth, urbanisation, and climate pressures, wastewater reclamation and reuse is rapidly becoming a key component of sustainable water management. Recent studies emphasise new technologies, optimisation and control, emerging contaminants, and system-level policy integration as leading fronts of research.

Technological innovations and treatment processes

One prominent trend is the advancement of hybrid and intensified treatment schemes to achieve high-quality reclaimed water suitable for various reuse applications. Shamshad et al. (2025) review both conventional and emerging treatment technologies – from activated sludge, membrane bioreactors (MBRs), constructed wetlands, to advanced oxidation and reverse osmosis – highlighting integration with renewable energy and digital monitoring for enhanced sustainability.

In particular, direct potable reuse (DPR) and indirect potable reuse (IPR) are gaining attention, with focus on ensuring robust multi-barrier safety against pathogens, chemicals, and micropollutants. Abbaszadegan et al. (2025) emphasise viral pathogen removal and per- and polyfluoroalkyl substances (PFAS) as urgent targets for reclamation systems. Mizyed (2025) proposes strategic frameworks for reusing partially treated wastewater (RPTWW), assessing the feasibility and impacts of reuse with lower levels of treatment in appropriate non-potable applications, to reduce energy and cost burdens. AI and data-driven approaches are also entering the domain. Liu et al. (2025) discuss AI-driven solutions for wastewater treatment, optimisation, and agricultural reuse, aiming to improve efficiency, predictive control, and system adaptability under variable loads.

Disaster and water microbiology

Disasters, including floods, hurricanes, storms, earthquakes, and extreme precipitation events, profoundly disrupt water systems, sanitation infrastructure, and water supply. In such settings, changes in microbiological water quality often lead to outbreaks of waterborne disease, challenges in water treatment, and long-term public health risks. The emerging field of “disaster and water microbiology” seeks to understand how disasters shift microbial ecology, pathogen dynamics, and vulnerability in water environments.

Recent research has focused on (1) how extreme events alter pathogen occurrence and distribution, (2) improved monitoring technologies for rapid detection in disrupted settings, and (3) resilience strategies and emergency response protocols to safeguard microbial water quality.

Disaster-driven shifts in microbial water quality

FLOOD AND HEAVY PRECIPITATION

One of the most studied phenomena is the impact of flooding and heavy rainfall on drinking water systems. A recent large-scale U. analysis (2000–2019) showed that following a flood or extreme precipitation event, the probability of detecting total coliform bacteria increased by 14–25%, and *E. coli* detection rose by 17–26% (USEPA, 2024). These events also triggered elevated formation of disinfection byproducts (DBPs) such as trihalomethanes (TTHM) and haloacetic acids (HAA5) due to elevated organic load in source waters and distribution systems. The impacts were observed in both surface- and groundwater systems and were more severe in smaller systems.

In European contexts, a 2024 study investigating flooding in Wrocław, Poland, found increased human health risk associated with microbial contamination in recreational waters in flooded zones. Some potentially pathogenic bacteria were also present in adjacent non-flooded areas, indicating spatial spread of risk (Ploneczka-Janeczko et al., 2025).

HURRICANES, STORMS, AND INFRASTRUCTURE DAMAGE

In the wake of hurricanes, shifts in microbial composition, increased pathogen loads, and water distribution failures are common. In Bangladesh, 2024 floods severely challenged public health systems, with elevated waterborne disease risks, highlighting urgent needs for microbial risk management in disaster responses (Rupa et al., 2024).

ADVANCES IN MONITORING AND RAPID DETECTION

A major challenge in post-disaster scenarios is timely microbial water quality assessment under adverse conditions. A variety of approaches exist:

- **Automated on-site microbial monitoring:** Reviews highlight progress in portable sensors, in situ platforms, and automated detection systems to allow near real-time assessment of microbial water quality in the field (Burnet et al., 2025).
- **Real-time monitoring technologies:** New devices enable rapid quantification of microbial contamination, reducing dependence on slow lab analysis (Dabrowska et al., 2024).
- **Flow cytometry and fingerprinting:** Cutting-edge methods (e.g. flow cytometric fingerprinting) can capture shifts in water microbiome communities across entire distribution systems, which is valuable especially when pathogen concentrations are low or spatially heterogeneous (Pluym et al., 2024).
- **Microbiological monitoring in humanitarian WASH settings:** In post-disaster and low-resource contexts, water quality monitoring (especially for microbes) is increasingly being emphasised as a critical component of effective water, sanitation, and hygiene (WASH) interventions (Lancaster et al., 2023).

Recommendations

MST

MST faces key challenges in environmental applications. Decay and transport modelling of markers remains underdeveloped, limiting confidence in quantitative source apportionment over time and distance. Marker universality and cross-reactivity pose issues, as host-associated markers vary geographically and may amplify non-target hosts. Metagenome-based MST adds complexity, requiring robust bioinformatics pipelines, reference libraries, and reproducibility frameworks, while sequencing approaches struggle with high detection limits. Integration with health risk models like QMRA is improving but still nascent. Standardisation across labs is essential. MST is evolving toward holistic, data-rich approaches combining marker- and community-based methods linked to human health outcomes.

AMR in the water environment

Despite progress, wastewater-based AMR research faces major challenges. Linking ARG signals to real health risks remains difficult, as detection does not guarantee infection or gene transfer, requiring better predictive models and functional assays. Lack of standardisation in sampling and analysis limits comparability, while high costs and scalability issues hinder adoption in low-income regions. Limited longitudinal monitoring constrains understanding of temporal dynamics, and integrative One Health approaches remain underdeveloped. Current trends emphasise holistic, risk-oriented strategies, leveraging advanced genomics, AI modeling, and innovative treatment technologies to mitigate resistance dissemination and strengthen public health resilience.

Wastewater reclamation and reuse

Despite progress in wastewater reuse, key challenges persist. Contaminants of emerging concern such as PFAS, pharmaceuticals, endocrine disruptors, and microplastics require better treatment, monitoring, and risk assessment. Ensuring safety, especially for potable reuse, demands reliable, cost-effective verification through real-time sensors and validation frameworks. Energy-intensive processes like reverse osmosis raise economic and carbon trade-offs, while public acceptance and governance call for transparent communication and adaptive regulations. Scalable, low-cost solutions are vital for low-income settings. Research increasingly focuses on integration and AI-driven optimisation, shifting from conventional treatment to transformative reuse systems that prioritise safety, efficiency, affordability, and resilience amid growing freshwater pressures.

Disaster and water microbiology

Research on resilience and preparedness in water microbiology focuses on maintaining safety during extreme events through robust system design, redundancy, and modular components. Just-in-time monitoring networks with real-time sensors and early-warning systems are being developed, while microbial risk modelling incorporates disaster scenarios into quantitative frameworks. Understanding shifts in entire microbial communities, not just pathogens, is critical for predicting opportunistic dynamics. Equity remains central, driving scalable, low-cost solutions for vulnerable regions. As floods and storms increasingly disrupt water quality and strain treatment systems, rapid detection technologies and adaptive protocols are emerging, with future priorities centered on resilience planning and democratised monitoring.

Conclusions

Health-related water microbiology is transitioning toward integrated, data-driven, and risk-oriented approaches to safeguard public health. Advances in MST, AMR monitoring, and wastewater reuse technologies are enabling more precise source identification, resistance mitigation, and safe resource recovery. However, persistent challenges – such as standardisation, cost, scalability, and equity – require global collaboration and adaptive governance. Disaster resilience research underscores the need for robust infrastructure, real-time monitoring, and inclusive strategies for vulnerable communities. Moving forward, coupling advanced genomics, AI, and predictive modeling with ethical frameworks will be critical to building resilient, sustainable water systems that address both emerging threats and long-term health security.

References

Abbaszadegan et al., Water Reuse – Retrospective study on sustainable future prospects. *Water*, 17(6), 789, 2025.

Burch et al., Quantitative microbial risk assessment with microbial source tracking for mixed fecal sources contaminating recreational river waters, Iowa, USA. ACS ES&T *Water*, 4(7), 2789-2802, 2024.

Burnet et al., Automation of on-site microbial water quality monitoring from source to tap: Challenges and perspectives. *Water Research*, 274, 123121, 2025.

Calero-Caceres et al., Advances and challenges in assessing antimicrobial resistance in environmental settings. *Current Opinion in Environmental Science & Health*, 41, 100571, 2024.

Corbeil et al., Marker- and microbiome-based microbial source tracking evaluation of bather health risks from fecal contamination in Galveston, Texas. *Water*, 17(15), 2310, 2025.

Dabrowska et al., Expanding access to water quality monitoring with the open-source WaterScope testing platform. *npj Clean Water,* 7, 68, 2024.

Demeter et al., Have genetic targets for faecal pollution diagnostics and source tracking revolutionized water quality analysis yet? *FEMS Microbiology Reviews*, 47(4), fuad028, 2023.

Demeter et al., Modelling the interplay of future changes and wastewater management measures on the microbiological river water quality considering safe drinking water production. *Science of the Total Environment*, 768, 144278, 2021.

Derx et al., 2021. Genetic microbial source tracking support QMRA modeling for a riverine wetland drinking water resource. *Fronters in Microbiology*, 12, 668778, 2021.

Dey et al., Antimicrobial resistant enteric bacteria are widely distributed among environmental water sources in Dhaka, Bangladesh. *npj Clean Water*, 8, 16, 2025.

Lan et al., A review on the prevalence and treatment of antibiotic resistance genes in hospital wastewater. *Toxics*, 13(4), 263, 2025.

Lancaster et al., Advanced preparedness for drinking water emergency: Ensuring safe microbial quality with rapid microbial source tracking and *E. coli* methods. *Environmental Advances*, 13, 100426, 2023.

Liu et al., AI-driven solutions in wastewater treatment and agricultural reuse systems: A comprehensive review. *Journal of Environmental Management*, 393, 127008, 2025.

Mizyed, A stragetic framework for reusing partially treated wastewater in agriculture: Viability and sustainability prospects. *Agricultural Water Management*, 317, 109676, 2025.

Monaco et al., Measuring water pollution effects on antimicrobial resistance through explainable artificial intelligence. *Environmental Pollution*, 367, 125620, 2025.

Murphy et al., The probability of detecting host-specific microbial source tracking markers in surface waters was strongly associated with mothod and season. *Microbiology Spectrum*, 13(2), e01972-24, 2025.

Naznine et al., Tracking antibiotic resistance in river waters: Sources, key microbe, and detection techniques. *The Microbe*, 7, 100386, 2025.

Ouyang et al., Recent advances in environmental antibiotic resistance genes detection and research focus: From genes to ecosystems. *Environmental International*, 191, 108989, 2024.

Paruch and Paruch, Current status of microbial source tracking applications in constructed wetlands serving as nature-based solutions for water management and wastewater treatment. *Environmental Pollution*, 351, 124076, 2024.

Ploneczka-Janeczko et al., Epidemiological insight into bacterial risk associated with flooded areas of city agglomeration (Wroclaw, Ploand, 2024). *Scientific Reports*, 15, 18182, 2025.

Pluym et al., Microbial drinking water monitoring now and in the future. *Microbial Biotechnology*, 17(7), e14523, 2024.

Rupa et al., Addresssing public health risks: Strategies to combat infectious diseases after the August 2024 floods in Bangladesh. *Journal of Preventive Medicine and Public Health*, 57(6), 600–603.

Ruti et al., Performance evaluation and application of human- and animal-specific microbial source tracking markers in river water in West Java, Indonesia. *Environmental Pollution*, 384, 126979, 2025.

Shamshad et al., Innovative approaches to sustainable wastewater treatment: a comprehensive exploration of conventional and emerging technologies. *Environmental Science Advances*, 4, 189–222, 2025.

Sefcik et al., Tracking the culprits: Microbial source tracking uncovers elevated fecal indicators along the Texas coast. *Advances in Microbiology*, 15(4), 217-231, 2025.

Talat et al., Antimicrobial resistance transmission in the environmental settings through traditional and UV-enabled advanced wastewater treatment plants: A metagenomic insight. *Environmental Microbiome*, 20, 27, 2025.

The Water Research Foundation, Critical evaluation and assessment of health and environmental risks from antibiotic resistance in reuse and wastewater. Link: https://www.waterrf.org/research/projects/critical-evaluation-and-assessment-health-and-environmental-risks-antibiotic?utm_source=chatgpt.comUnno et al., Fecal pollution: New trends and challenges in microbial source tracking using next-generation sequencing. *Environmental Microbiology*, 20(9), 3132-3140, 2018.

USEPA, When it rains, it pours: Severe weather events, flooding, and drinking water quality. https://www.epa.gov/system/files/documents/2024-12/2024-12.pdf?utm_source=chatgpt.com

Yang et al., Profiles of antibiotic resistome risk in diverse water environments. *Communications Earth & Environment*, 6, 158, 2025.

Zhao et al., Increased risk of antibiotic resistance in surface water due to global warming. *Environmental Research*, 263 (2), 120149.

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Drinking water safety trends and challenges from a risk management perspective

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Key terminology

- **Water safety plan (WSP):** A proactive risk assessment and risk management approach, that encompasses the entire drinking-water supply from catchment to consumer
- **Self-supply:** A water supply system that is privately financed, constructed, operated, and maintained by individuals or small groups to meet their own water needs
- **Climate-resilient water safety plan:** An update to WSP guidance that integrates climate change impacts into the original WSP framework
- **Sanitation safety plan:** A management approach, parallel to WSPs, that systematically identifies and manages health risks along the entire sanitation service chain, from containment to disposal

Introduction

Status

According to the United Nations, three-quarters of the world's population uses a safely managed drinking water service as of 2025 (UN-Water, 2025b). Within this globally aggregated statistic, the term "safely managed" covers variable types of water service delivery to different people. The Sustainable Development Goal (SDG) indicator 6.1.1 directly measures access to a structurally "improved" drinking water source that is located on their household premises, available when needed, and free of fecal and priority chemical contamination (UN-Water, 2025a). This represents a step forward from "unimproved" water sources, such as water fetched from a lake surface or a hand-dug well distant to one's home.

Another prominent global concept, "water safety plans" (WSPs), represents the use of a "proactive risk assessment and risk management approach to help ensure drinking-water safety, encompassing the entire drinking-water supply, from catchment to consumer" (WHO, 2023). WSPs have been recommended by the World Health Organization since 2004 for all water supplies as the most effective means of consistently ensuring the safety of a drinking-water supply (WHO, 2022a). According to a global survey, WSPs were implemented, at least at pilot scale, in 93 of 118 responding countries, and about half had scaled the programming up to 10 or more water systems (WHO, 2017). Still, WSPs are not inherently required to achieve SDG 6.1: universal and equitable access to safe and affordable drinking water for all by 2030 (UN-Water, 2025b). Depending on one's interpretation, then, considering a water supply system optimised for safety could mean (1) a risk management framework implemented in practice for the whole water system, (2) some programming to control operations for parts of the water system, or (3) testing for some indicators of finished water quality. Notably, each of these statuses produces a vastly different level of system oversight.

Primary challenge

In practice, water supply management approaches reflect global variability. Adoption of the water safety plan approach has been uneven, with some world regions and countries making larger strides than others (WHO, 2017). For example, Australia, Southeast Asia, and northern Europe have witnessed more pervasive uptake, spurred forward by policy recognition of the shortcomings of alternative approaches (Gunnarsdottir et al., 2023; Hrudey et al., 2006; Sutherland and Payden, 2017). As the later examples show, the rate of application does not necessarily depend solely on country income levels, but also the complexity of the regulatory environment, the dispersion

of the serviced population, organisational dynamics, and political will (Amjad et al., 2016; Duku et al., 2024; Omar et al., 2017).

Ensuring that known good practices, such as WSPs, continue to proliferate across the global water supply sector represents a primary ongoing challenge, also considering regular interruptions due to political instability, humanitarian crises, and disease outbreaks (JMP, 2021, 2025). Although the collective work to adapt, scale, and sustain universal application of WSPs remains incomplete, implementation techniques borrowed from the healthcare workforce could aid effective programme replication among water and sanitation practitioners (Haque and Freeman, 2021). For example, one popular implementation framework urges managers to consider all relevant aspects of the programming context in a human-centered manner, such as leadership at different levels, relational networks, mission alignment, market pressure, tension for change, information infrastructure, performance measurement, and incentives (Damschroder et al., 2022).

Key insights: global trends affecting water safety planning

Weak system linkages

Observed from afar, our drinking water sources clearly remain closely connected with larger-scale water cycles. Although drinking water safety management offers intervention at a critical step between the water source and consumer, optimally such programming would interlink with corresponding programmes addressing pollution reduction, solid waste and wastewater management, commercial activities, wildlife management, recreation management, population dynamics, disease surveillance, and other proactive planning. This need has sometimes been addressed under module nine of the WSP approach, called "supporting programmes" (WHO, 2023), although water utilities tend to focus more inwardly on aspects under their explicit control.

Guidance exists for better linking the drinking water risk management approach to different portions of the water system, such as watershed management (WHO, 2016) and sanitation (WHO, 2022b). Nevertheless, responsibility for ensuring these cross-linkages may be less apparent. Even within a drinking water supply system, some iterations of WSPs miss, or focus closely only on, portions of the system, such as the water treatment plant or water distribution to households. This partially complete status makes sense during a growth phase of WSP uptake; however, utility managers must continue to persist at connecting water supply planning with other influential systems to "close the loop."

Lags in climate resilience

Climate shifts remain a key challenge, as water supply and wastewater treatment infrastructure can easily become overwhelmed by severe storms or droughts of a scale that simply did not exist at the time of their construction. No longer a future scenario, intensified events arrive regularly. Accelerated climate change especially concerns the water supply industry, where infrastructure lasts for decades to centuries, and early replacement or relocation would be cost-prohibitive. Infrastructure management approaches, fortunately, remain flexible (Rickert et al., 2019). WSP guidance, and lists of potential climate-related hazards, have been updated to recognise climate risks via several pilot efforts, for instance in Nepal, Bangladesh, Ethiopia, and Tanzania (WHO and IWA, 2025a).

Still, climate preparedness remains an abstract, intimidating, or low-priority topic for many practitioners around the globe. Improved training access and an increased number of tangible case examples in world regions with different types of climates could help to spur consideration and imitation of climate preparedness steps among other water suppliers in the same zones.

Underserved populations

While global access to safe water continues to make strides, less visible and tangible "communities" remain harder to serve than those "on the grid" (Brown et al., 2023). Examples of underserved populations include unhoused people in major cities (Avelar Portillo et al., 2023), people with disabilities (Banks et al., 2019), and those denied services due to a legacy of racism or social exclusion (Stillo and MacDonald Gibson, 2017). In addition, ensuring water safety for transient groups, such as livestock pastoralists (Whitley et al., 2019), seasonal agricultural workers (Rodríguez-Guerrero et al., 2024), and ethnic minorities (Anthonj et al., 2025) remains challenging. Tailored attention and partnerships with these groups can help to break the scourge of invisibility, identifying appropriate and socially sensitive approaches to ensuring safe water access.

Alternative water sourcing

In low- and middle-income country contexts, as well as peri-urban and rural areas in high-income countries, water suppliers have seen a trend toward households electing to use self-supply rather than centralised water services (Foster et al., 2021). This choice occurs in part due to unsatisfactory water services, for example due to intermittency or poor water quality. While the phenomenon injects private finance into the safe water supply equation, it also results in more people for whom the water supply is not professionally managed. Legally, local public entities are rarely required to provide proactive oversight or testing services for households using self-supplied water (Imgrund et al., 2011). Assigning water

supply management responsibilities to households with often inconsistent behaviours leaves people at risk of unmanaged contamination (Murray et al., 2020).

Another trend exists toward reselling municipal water as "packaged water" in jugs, bottles, sachets, or other containers. The concept that packaged water is always safer to drink than piped water poses a challenge, because the true difference in quality varies greatly (Diduch et al., 2013; Vedachalam et al., 2017; Williams et al., 2015). Packaged water often has less stringent regulatory oversight, although it may have a more favorable taste, temperature, or marketing. Resellers may simply rebrand municipal tap water and sell it at a higher cost, although some add additional treatment and process control steps that legitimately improve safety. In an attempt to render higher profits or out-compete others, at worst, untrustworthy resellers may seek to frighten consumers with misinformation. The spread of unvalidated claims in advertising and on social media may leave poorly informed consumers paying much higher out of pocket costs for water, while putting their family's health and safety at risk. For instance, some consumers travel to collect untreated "natural" spring water for drinking, even when other professionally managed service options exist (Patton et al., 2020).

The question remains: how can governments best regulate, permit, inspect, and ensure trustworthy alternative water supplies? In low-regulatory environments, pressure for safety assurances may need to come from within the industry itself. Preferably, local government entities or university extensions, in partnership with well-resourced centralised water suppliers, might provide outreach and technical assistance with alternative water supply maintenance and testing.

Water safety beyond the home

Households are not the only location where people consume water, and the WHO/UNICEF global monitoring entity (Joint Monitoring Programme for Water Supply, Sanitation and Hygiene) clearly recognises schools and healthcare facilities as other critical service locations that need to ensure water safety (UN-Water, 2025a). Sensitive locations in the service area may be considered within the water provider's WSP (WHO, 2023), although depending on the size and location of these facilities, they might prefer to manage their own independent water supply.

Recognition that people in urban areas spend much of their time living and working in buildings led to development and recommendation of a building-level WSP approach (WHO, 2011). This guidance expansively considers time spent in childcare and healthcare facilities, as well as retirement homes, prisons, and short-term lodgings and campsites. Future adaptations and iterations could extend the reach of water safety planning across even more distributed spaces, such as temporary shelters, wilderness recreation areas, or transportation hubs and spokes.

Case studies

Creating policy cohesion in the Americas

Viewing a map of WSP uptake in North America, one country stands out as having no WSP implementation (WHO, 2017). In this case, the highly regulated national environment of the United States has forestalled policy consideration of other global water safety recommendations (Baum and Bartram, 2017). The dominant federal mandates emphasise compliance (finished water quality) monitoring, and water suppliers may not have the capacity to take on additional proactive risk management activities (Amjad et al., 2016). A voluntary subscription programme, the Partnership for Safe Water, redoubles the focus on finished water quality evaluation and water treatment improvement (AWWA, 2025). Legislative updates under America's Water Infrastructure Act of 2018 require vulnerability assessment for natural hazards and malevolent acts; however, differences such as the limited scope and staff involvement leave water suppliers somewhat out of step with the global WSP recommendations. Initial analyses point to potential benefits from a holistic process that would consolidate efforts and bridge gaps among various siloed management approaches (Baum et al., 2015; Setty et al., 2019).

By comparison, Latin American and Caribbean countries have more extensively focused on WSP implementation (WHO, 2017). Still, a status report covering Argentina, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, Honduras, Jamaica, México, Perú, and Uruguay found that many countries had not compiled a comprehensive national policy on drinking water quality, with elements of a safe water framework instead dispersed across various legal and technical instruments (OPS, 2021). While most countries had defined water quality parameters using WHO guidelines and encouraged monitoring, the integration of health- or risk-based methods remained inconsistent. Recommendations included to:

- Develop standalone national policies to integrate all elements of the water safety framework;
- Establish methodologies to incorporate risk management when defining water quality parameters;
- Promote training programs and action plans to support WSP implementation, and
- Enhance surveillance and information systems to support decision-making and planning (e.g. through consolidated national reports).

Spurring scale-up in Ghana

Ghana's National Drinking Water Quality Management Framework began requiring WSPs in 2015, offering insight into the challenges facing implementation rollout in numerous countries. The critical step toward national adaptation of the global guidance should in theory galvanise scale-up, yet as of 2024, only three of 88 urban water systems, 177 of 1,022 small-town systems, 46 safe water enterprise systems, and no community-managed systems had initiated the WSP process (Duku et al., 2024). An analysis of the political economy for rural water services pointed to several issues, for example: weak line ministry capacity, insufficient local government staffing, lack of clarity in legal policies, ill-defined and overlapping service areas, inconsistent water tariff frameworks, and localised elite capture (USAID, 2025).

Under Ghana's 2024 update to the National Water Policy (MSWR, 2024), regulatory reforms that include stronger enforcement mechanisms and internal and third-party auditing of progress toward the completion of all WSP steps could greatly support implementation progress. Country-to-country peer support, also called "water operator partnerships," can likewise lend support by matching utilities more experienced with WSPs to those earlier in the process (Sheehan et al., 2023).

Piloting a combined approach in Serbia

Available data show that non-compliance rates for *E. coli*, arsenic, and nitrates are vastly higher in rural water systems in Serbia (WHO, 2025). Recognising that applying the water and sanitation safety planning approaches separately might pose a challenge (WHO, 2022b, 2023), experts facilitated an integrated approach for three small systems in rural areas (van den Berg et al., 2023). Combining the two approaches started with aligning and integrating the steps or modules from each set of guidance into six steps that addressed both the drinking water and wastewater system. A workshop and peer-learning visits also took place across sites.

The pilot implementation effort contributed to a better understanding of both systems among the staff and improved communication and collaboration between the typically separate drinking-water and sanitation domains. The WSP improvement plans triggered communities to initiate some immediate changes, despite not having a formal budget in place. Challenges included documenting decentralised facilities (i.e. septic tanks) and integrating maps. Key recommendations to replicate the approach include involving facilitators, building upon established daily practices, and creating simplified guidance, easy-to-use training materials, and editable templates.

Onboarding buildings in Hong Kong

Hong Kong's skyline showcases scores of multistory buildings. As such, the Water Supplies Department created WSP templates in 2017 for general buildings such as residential or office buildings, as well as special developments, such as schools, elderly care homes, and hospitals (Choy, 2025). Risk assessments identify specific locations within each building appropriate for regular inspections, for instance to check pumps, backflow prevention devices, water tanks, and point-of-use devices such as water fountains. The Department likewise trains the trainers responsible for accreditation of plumbing practitioners, and maintains a directory of qualified professionals. Their voluntary programme involves building owners and managers, who receive fee-free certification and site visits to check on their implementation progress. The Department offers financial assistance to building owners in need and broadly publicises their efforts. These efforts have expanded coverage to approximately 4,700 buildings, covering about 40 percent of households in the city.

Recommendations

While in theory a well-organised approach to WSPs sounds ideal, waiting for abundant financial resources and absolute organisational readiness to undertake a WSP could delay progress indefinitely. The formal guidance recommends that getting started is preferable to doing nothing (WHO, 2023). Even tentative initial steps can elicit helpful knowledge, including communication pitfalls, historic failures, or unmapped risks.

The open-source Water Safety Portal, a resource library sponsored by the International Water Association and World Health Organization, has grown to contain extensive guidance documents and examples from practice (WHO and IWA, 2025b). The "roadmap to supporting resources" offers a great starting point for new learners (WHO, 2024b). Many crowdsourced resources have been adapted to specific water system types, aspects of water systems, cultural contexts, languages, or critical issues. IWA and WHO continue to update the official open-access implementation guidance for both small and large water systems, while the International Organization for Standardization (ISO 22000) offers related subscription resources (ISO, 2024; WHO, 2023, 2024a).

If practitioners cannot access guidance relevant to their situation, a logical first step is to work on adapting the closest available resources. This step toward adaptation can be undertaken from a national policy, professional association, academic, or even grassroots starting point. The average practitioner should not hesitate to consider existing guidance and then potentially adjusting it to fit local needs, albeit without discarding core programme components. For instance, a water supplier might choose to:

- Determine which of their existing activities already address portions of the WSP steps versus what might be missing,
- Create added roles or procedures for involving culturally important stakeholders such as traditional or religious leaders, or
- Transcribe guidance terminology to match the lay language commonly used within their community of practice.

Those well underway with the WSP process can ensure continual improvement by adopting a growth mindset (i.e. "we learn new things every day that help us to adjust our practices") versus a fixed mindset (i.e. "we completed our plan on paper, well done us!"). An often-overlooked step (WHO, 2017) is to partner with external auditors and local research institutions to gain an honest and independent look at what has gone well or poorly, using a "no blame" approach (WHO, 2015). At their core, WSPs are less about documentation and more about developing professionalism, foresight, communication, self-evaluation, and partnerships among the humans who work to ensure water safety for their neighbors.

Conclusions

Despite the resource challenges facing global communities and growing pressure on water resources, many water professionals around the globe look to WSPs as the means to get ahead of water quality issues, to reinforce beneficial habits, to prevent service delivery failures, and to (frankly) sleep better at night! Moving forward, the water supply management sector must continue to professionalise, to replicate effective practices at larger scales, at a measured pace, and to ultimately service all water consumers where they are.

References

Amjad, U. Q., Luh, J., Baum, R., & Bartram, J. (2016). Water safety plans: Bridges and barriers to implementation in North Carolina. *Journal of Water and Health*, 14(5), 816–826. https://doi.org/10.2166/wh.2016.011

Anthonj, C., Setty, K., Hoeser, C., Brown, J., Ihnacik, L., & Poague, K. (2025). Assessing water and health insecurity in informal settlements: Bringing Europe's invisible, marginalized Roma communities into focus. A systematic scoping review. *Social Science & Medicine*, 384, 118526. https://doi.org/10.1016/j.socscimed.2025.118526

Avelar Portillo, L. J., Kayser, G. L., Ko, C., Vasquez, A., Gonzalez, J., Avelar, D. J., Alvarenga, N., Franklin, M., & Chiang, Y.-Y. (2023). Water, Sanitation, and Hygiene (WaSH) insecurity in unhoused communities of Los Angeles, California. *International Journal for Equity in Health*, 22, 108. https://doi.org/10.1186/s12939-023-01920-8

AWWA. (2025). *Partnership for Safe Water*. American Water Works Association. https://www.awwa.org/programs/partnership-for-safe-water/

Banks, L. M., White, S., Biran, A., Wilbur, J., Neupane, S., Neupane, S., Sharma, A., & Kuper, H. (2019). Are current approaches for measuring access to clean water and sanitation inclusive of people with disabilities? Comparison of individual- and household-level access between people with and without disabilities in the Tanahun district of Nepal. *PLOS ONE*, 14(10), e0223557. https://doi.org/10.1371/journal.pone.0223557

Baum, R., Amjad, U., Luh, J., & Bartram, J. (2015). An examination of the potential added value of water safety plans to the United States national drinking water legislation. *International Journal of Hygiene and Environmental Health, Sixth European PhD Students Workshop: Water and Health - Cannes 2014*, 218(8), 677–685. https://doi.org/10.1016/j.ijheh.2014.12.004

Baum, R., & Bartram, J. (2017). A systematic literature review of the enabling environment elements to improve implementation of water safety plans in high-income countries. *Journal of Water and Health*, 16(1), 14–24. https://doi.org/10.2166/wh.2017.175

Brown, J., Acey, C. S., Anthonj, C., Barrington, D. J., Beal, C. D., Capone, D., Cumming, O., Pullen Fedinick, K., MacDonald Gibson, J., Hicks, B., Kozubik, M., Lakatosova, N., Linden, K. G., Love, N. G., Mattos, K. J., Murphy, H. M., & Winkler, I. T. (2023). The effects of racism, social exclusion, and discrimination on achieving universal safe water and sanitation in high-income countries. The Lancet. *Global Health*, 11(4), e606–e614. https://doi.org/10.1016/S2214-109X(23)00006-2

Choy, T. (2025, August). *Hong Kong's Experience of Implementing Water Safety Plan for Buildings (WSPB)*. Water Safety Planning Specialty Group Management Committee.

Damschroder, L. J., Reardon, C. M., Opra Widerquist, M. A., & Lowery, J. (2022). Conceptualizing outcomes for use with the Consolidated Framework for Implementation Research (CFIR): The CFIR Outcomes Addendum. *Implementation Science*, 17(1), 7. https://doi.org/10.1186/s13012-021-01181-5

Diduch, M., Polkowska, Ż., & Namieśnik, J. (2013). Factors affecting the quality of bottled water. *Journal of Exposure Science & Environmental Epidemiology,* 23(2), 111–119. https://doi.org/10.1038/jes.2012.101

Duku, G. A., Appiah-Effah, E., Gyamfi, C., & Nyarko, K. B. (2024). Ghana's water safety journey: A review of efforts toward a risked-based water quality management. *Journal of Water and Health*, 22(12), 2370–2384. https://doi.org/10.2166/wh.2024.371

Foster, T., Priadi, C., Kotra, K. K., Odagiri, M., Rand, E. C., & Willetts, J. (2021). Self-supplied drinking water in low- and middle-income countries in the Asia-Pacific. *Npj Clean Water*, 4(1), 37. https://doi.org/10.1038/s41545-021-00121-6

Gunnarsdottir, M. J., Gardarsson, S. M., Eriksson, M., Albrechtsen, H.-J., Bergkvist, K. S. G., Rossi, P. M., Matilainen, R., Hansen, L. T., Jensen, P. E., Maréchal, J. Y. A., Myrmel, M., Kalheim, F. C., Persson, K. M., Bjerkén, A., & Bartram, J. (2023). Implementing risk-based approaches to improve drinking water quality in small water supplies in the Nordic region – barriers and solutions. *Journal of Water and Health*, 21(12), 1747–1760. https://doi.org/10.2166/wh.2023.088

Haque, S. S., & Freeman, M. C. (2021). The applications of implementation science in water, sanitation, and hygiene (WASH) Research and practice. *Environmental Health Perspectives*, 129(6), 065002. https://doi.org/10.1289/EHP7762

Hrudey, S. E., Hrudey, E. J., & Pollard, S. J. T. (2006). Risk management for assuring safe drinking water. *Environment International*, 32(8), 948–957. https://doi.org/10.1016/j.envint.2006.06.004

Imgrund, K., Kreutzwiser, R., & De Loë, R. (2011). Influences on the water testing behaviors of private well owners. *Journal of Water and Health*, 9(2), 241–252. https://doi.org/10.2166/wh.2011.139

ISO. (2024). ISO 22000:2018. https://www.iso.org/standard/65464.html

JMP. (2021). *Progress on household drinking water, sanitation and hygiene 2000—2020*. WHO/UNICEF Joint Monitoring Program for Water Supply, Sanitation and Hygiene. https://www.unwater.org/publications/who/unicef-joint-monitoring-program-water-supply-sanitation-and-hygiene-jmp-progress-0

JMP. (2025). *Progress on household drinking water, sanitation and hygiene 2000–2024: Special focus on inequalities*. Geneva: World Health Organization (WHO) and the United Nations Children's Fund (UNICEF).

MSWR. (2024). *Ghana National Water Policy*. Government of Ghana: Ministry of Sanitation and Water Resources. https://www.ircwash.org/sites/default/files/ghana_national_water_policy_updated_version_2024.pdf

Murray, C. J., Olson, A. L., Palmer, E. L., Yang, Q., Amos, C. I., Johnson, D. J., & Karagas, M. R. (2020). Private well water testing promotion in pediatric preventive care: A randomized intervention study. *Preventive Medicine Reports*, 20, 101209. https://doi.org/10.1016/j.pmedr.2020.101209

Omar, Y. Y., Parker, A., Smith, J. A., & Pollard, S. J. T. (2017). Risk management for drinking water safety in low and middle income countries—Cultural influences on water safety plan (WSP) implementation in urban water utilities. *Science of the Total Environment*, 576, 895–906. https://doi.org/10.1016/j.scitotenv.2016.10.131

OPS. (2021). *Situación del marco para la seguridad del agua de consumo humano en América Latina y el Caribe*. Organización Panamericana de la Salud. https://doi.org/10.37774/9789275324554

Patton, H., Krometis, L.-A., & Sarver, E. (2020). Springing for safe water: drinking water quality and source selection in Central Appalachian communities. *Water*, 12(3), 888. https://doi.org/10.3390/w12030888

Rickert, B., van den Berg, H., Bekure, K., Girma, S., & de Roda Husman, A. M. (2019). Including aspects of climate change into water safety planning: Literature review of global experience and case studies from Ethiopian urban supplies. International *Journal of Hygiene and Environmental Health*, 222(5), 744–755. https://doi.org/10.1016/j.ijheh.2019.05.007

Rodríguez-Guerrero, L. A., Pérez-Urdiales, I., Escrig-Piñol, A., Jiménez-Lasserrotte, M. del M., Pastor-Bravo, M. del M., Mateos, J. T., & Briones-Vozmediano, E. (2024). Water insecurity among seasonal agriculture workers: Perspectives from Spanish professionals. *International Journal for Equity in Health*, 23, 31. https://doi.org/10.1186/s12939-024-02112-8

Setty, K., McConnell, R., Raucher, R., & Bartram, J. (2019). Comparative evaluation of risk management frameworks for U.S. source waters. *AWWA Water Science*, 1(1), e1125. https://doi.org/10.1002/aws2.1125

Sheehan, D., Fasham, P., McKeown, R. M., & Jayaratne, A. (2023). Development of a tool to support operationalising water safety plans: Experiences from a national water utility in Ghana. Journal of Water and Health, 21(12), 1761–1771. https://doi.org/10.2166/wh.2023.100

Stillo, F., & MacDonald Gibson, J. (2017). Exposure to contaminated drinking water and health disparities in North Carolina. *American Journal of Public Health*, 107(1), 180–185. https://doi.org/10.2105/AJPH.2016.303482

Sutherland, D., & Payden. (2017). Observations and lessons learnt from more than a decade of water safety planning in South-East Asia. *WHO South-East Asia Journal of Public Health*, 6(2), 27. https://doi.org/10.4103/2224-3151.213788

UN-Water. (2025a). *Indicator 6.1.1 "Proportion of population using safely managed drinking water services."* UN-Water. https://www.unwater.org/our-work/sdg-6-integrated-monitoring-initiative/indicator-611-proportion-population-using-safely

UN-Water. (2025b). *Progress on Drinking Water (SDG target 6.1)*. https://sdg6data.org/en/indicator/6.1.1

USAID. (2025). *Political economy analysis of rural water performance under different management arrangements in Ghana*. USAID Rural Evidence and Learning for Water (REALWater) Project. https://www.aguaconsult.co.uk/post/rural-water-service-delivery-it-s-the-politics-stupid

van den Berg, H., Rickert, B., Lock-Wah-Hoon, J., Jovanovic, D., Bijelovic, S., Gligorijevic, S., Karadzic, V., Vasic, M., & de Roda Husman, A. M. (2023). Experiences from integrating water and sanitation safety planning in small systems in rural Serbia. *Journal of Water and Health*, 21(12), 1772–1783. https://doi.org/10.2166/wh.2023.204

Vedachalam, S., MacDonald, L. H., Omoluabi, E., OlaOlorun, F., Otupiri, E., Schwab, K. J., & on behalf of PMA2020 Investigators. (2017). The role of packaged water in meeting global targets on improved water access. *Journal of Water, Sanitation and Hygiene for Development,* 7(3), 369–377. https://doi.org/10.2166/washdev.2017.155

Whitley, L., Hutchings, P., Cooper, S., Parker, A., Kebede, A., Joseph, S., Butterworth, J., Van Koppen, B., & Mulejaa, A. (2019). A framework for targeting water, sanitation and hygiene interventions in pastoralist populations in the Afar region of Ethiopia. *International Journal of Hygiene and Environmental Health*, 222(8), 1133–1144. https://doi.org/10.1016/j.ijheh.2019.08.001

WHO. (2011). *Water safety in buildings*. World Health Organization. https://www.who.int/publications/i/item/9789241548106

WHO. (2015). *A practical guide to auditing water safety plans*. https://www.who.int/publications/i/item/9789241509527

WHO. (2016). *Protecting surface water for health: Identifying, assessing and managing drinking-water quality risks in surface-water catchments*. World Health Organization. https://www.who.int/publications/i/item/9789241510554

WHO. (2017). *Global status report on water safety plans.* https://www.who.int/publications/i/item/WHO-FWC-WSH-17.03

WHO. (2022a). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. World Health Organization. https://www.who.int/publications/i/item/9789240045064

WHO. (2022b). *Sanitation safety planning*. World Health Organization. https://www.who.int/publications/i/item/9789240062887

WHO. (2023). *Water Safety Plan Manual: Step-By-step Risk Management for Drinking-water Suppliers* (2nd ed). World Health Organization.

WHO. (2024a). *Guidelines for drinking-water quality: Small water supplies*. https://www.who.int/publications/i/item/9789240088740

WHO. (2024b). *Water safety planning: A roadmap to supporting resources*. World Health Organization. https://www.who.int/publications/m/item/water-safety-planning-a-roadmap-to-supporting-resources

WHO. (2025). *Small-scale sanitation and drinking-water supply systems: Driving country action towards safer services*. WHO Regional Office for Europe. https://www.who.int/europe/publications/i/item/WHO-EURO-2025-12753-52527-81181

WHO & IWA. (2025a). *Water Safety Portal | Resource Categories Climate Resilience*. https://wsportal.org/resources/climate-resilience/

WHO & IWA. (2025b). *Water Safety Portal: Find WSP Resources*. https://wsportal.org/find-wsp-resources/

Williams, A. R., Bain, R. E. S., Fisher, M. B., Cronk, R., Kelly, E. R., & Bartram, J. (2015). A systematic review and meta-analysis of fecal contamination and inadequate treatment of packaged water. *PLOS ONE*, 10(10), e0140899. https://doi.org/10.1371/journal.pone.0140899

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Wastewater-based epidemiological surveillance

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Introduction

Wastewater-based epidemiological surveillance (WBES) has emerged as a transformative approach for public health monitoring, offering a cost-effective, non-invasive, and population-wide method to track infectious and non-communicable diseases. Unlike traditional clinical surveillance, which often relies on symptomatic individuals seeking care, WBES captures data from entire communities, including asymptomatic and pre-symptomatic cases. This capability became particularly evident during the COVID-19 pandemic, where wastewater monitoring provided early warnings of outbreaks and complemented clinical reporting systems.

The principle behind WBES is straightforward yet powerful: pathogens, pharmaceuticals, and biomarkers excreted by individuals enter wastewater systems, creating a composite signal of community health. Advances in molecular biology, sequencing technologies, and data analytics have enabled the detection of viral RNA, bacterial DNA, protein biomarkers, and even pharmaceutical metabolites in sewage. These developments have expanded WBES applications beyond infectious disease surveillance to include monitoring of chronic conditions such as cardiovascular disease, diabetes, and neurodegenerative disorders.

Recent methodological innovations have improved sensitivity and specificity. Techniques such as untargeted viral metagenomics (UVM), target enrichment sequencing (TES), and amplicon deep sequencing (ADS) allow comprehensive profiling of viral communities. Novel protocols like EPISENS-M have demonstrated strong correlations between wastewater viral loads and clinical case counts, enabling predictive modeling of disease trends. Furthermore, state-space models and Bayesian smoothing approaches have enhanced the reliability of wastewater-derived epidemiological indicators, such as the effective reproduction number (Re).

Beyond infectious diseases, WBES is increasingly applied to detect biomarkers for non-communicable diseases and pharmaceutical consumption patterns. Studies have identified protein biomarkers linked to COVID-19 and proposed urine-based indicators for Alzheimer's disease. Pharmaceutical metabolite analysis has proven effective for estimating community-level prevalence of chronic conditions, offering insights into drug usage and lifestyle trends.

Despite its promise, WBES faces challenges related to standardisation, ethical considerations, and infrastructure limitations. Harmonising sampling protocols and analytical methods is critical for comparability across regions. Ethical frameworks must address privacy concerns, data governance, and equitable access to benefits, particularly in underserved communities. Global initiatives, such as aircraft-based surveillance networks and airport monitoring, highlight WBES's potential for pandemic preparedness, but also underscore the need for international collaboration and governance.

In summary, WBES represents a paradigm shift in public health surveillance, bridging gaps in traditional systems and enabling proactive responses to health threats. Its continued evolution will depend on technological innovation, ethical stewardship, and global cooperation.

Key terminology

- Wastewater-based epidemiological surveillance: The monitoring and analysis of pathogens, chemicals, and pharmaceuticals in municipal wastewater to track population-level health trends, disease outbreaks, and substance use patterns.
- Effective reproduction number: The average number of secondary infections caused by a single infected individual in a population at a specific time, accounting for existing immunity and active control measures.
- Biomarkers: Molecular signatures, such as viral RNA, bacterial DNA, human metabolites, or chemical residues, excreted into sewage systems that serve as measurable indicators of disease prevalence, substance use, and overall population health.

Key insights

WBES has proven to be a versatile and scalable tool for health surveillance. Its ability to capture asymptomatic cases and provide near real-time data makes it invaluable for infectious disease monitoring. Methodological advancements, such as next-generation sequencing and sensitive RNA detection protocols, have significantly improved detection accuracy and predictive capabilities.

The scope of WBES now extends beyond communicable diseases. Research on protein biomarkers and pharmaceutical metabolites has opened avenues for monitoring chronic conditions and lifestyle trends. This expansion positions WBES as a holistic health surveillance system, capable of informing both acute outbreak responses and long-term public health strategies.

Global interest in WBES is growing, with proposals for international surveillance networks leveraging airports and aircraft wastewater. These initiatives aim to provide early warnings for pandemics, reinforcing WBES's role in global health security. However, challenges remain in standardising methodologies, ensuring data interoperability, and addressing ethical concerns such as privacy and equity. Without robust governance frameworks, WBES risks exacerbating social inequalities or misusing sensitive data.

Wastewater-based epidemiological surveillance and public health monitoring

The COVID-19 pandemic accelerated global efforts to utilise wastewater as a surveillance tool for infectious diseases. WBES enables near real-time community-level health monitoring by detecting genetic material, proteins, pharmaceuticals, and other biomarkers excreted by infected or affected individuals. Unlike traditional clinical surveillance, WBES offers cost-effective, non-invasive, and population-wide coverage, capturing symptomatic, pre-symptomatic, and asymptomatic cases alike. However, effective use of WBES requires rigorous scientific frameworks, technological standardisation, and ethical considerations. HRWM SG is currently leading the IWA WBES Cluster, and maintains a website to collect and share global information on wastewater surveillance (https://wastewaterbasedepidemiologicalsurveillance.net/).

Recent studies on WBES, covering advances in methodologies, biomarker discovery, modeling approaches, ethical frameworks, and applications to both communicable and non-communicable diseases, are summarised below.

Methodological innovations

Martínez-Puchol et al. (2020) compared three methods, untargeted viral metagenomics (UVM), target enrichment sequencing (TES), and amplicon deep sequencing (ADS), for detecting papillomaviruses, adenoviruses, and enteroviruses in urban sewage. UVM provided a full virome picture, including human, plant, and bacterial viruses. TES, using specific probes, was the best strategy for a broad view of human viruses, detecting high diversity and genome coverage across eight families. ADS offered the highest intra-family diversity for the target viruses and enabled subtyping of an outbreak-related enterovirus strain. Each method offers a different analytical level: TES for a broad human virus scope, UVM for a full virome, and ADS for detailed family-level diversity.

Ando and Reynolds (2024) proposed a framework to estimate the effective reproduction number *(Re)* directly from wastewater data even without shedding dynamics. Using state-space models to smooth data and reconstruct missing values, they demonstrated consistency between wastewater-derived *Re* and clinical *Re* for influenza A and SARS-CoV-2. Frequent sampling (≥3 times/week) was shown to improve precision. The method is particularly useful where clinical reporting is absent or incomplete.

John et al. (2024) assessed next-generation sequencing (NGS) methods for WBES. They compared shotgun metagenomics, targeted amplicon sequencing, and hybrid approaches. Each method showed trade-offs: shotgun sequencing provides broad detection but lower sensitivity for rare pathogens, while targeted methods enhance sensitivity but limit scope. Hybrid strategies were recommended for comprehensive monitoring.

Ando et al. (2023) developed EPISENS-M, a highly sensitive SARS-CoV-2 RNA detection protocol combining adsorption extraction, pre-amplification, and qPCR. This method correlated strongly (r = 0.94) with clinical cases in Sapporo and improved predictive modeling of COVID-19 incidence up to five days in advance

Amarasiri et al. (2021) reviewed the potential of environmental DNA/RNA (eDNA/eRNA) for pathogen and host/vector monitoring in aquatic systems. These methods allow rapid, non-invasive detection of pathogens and reservoirs, offering early warning for vector-borne and zoonotic diseases.

NEW BIOMARKERS

Devianto et al. (2024) identified wastewater protein biomarkers linked to COVID-19 incidence, supporting real-time disease monitoring. A companion systematic review and meta-analysis (Deveianto et al., 2023) catalogued 64 promising protein

biomarkers from urine and feces, including calprotectin and uromodulin, with applications to gastrointestinal, renal, and metabolic disorders. Armenta-Castro et al. (2024) proposed urine-based biomarkers for Alzheimer's disease (amyloid-β, tau, oxidative stress markers, and long non-coding RNAs). WBES could enable community-level screening of neurodegenerative disease prevalence, though challenges remain regarding biomarker stability and detection sensitivity. Ceolotto et al. (2024) developed workflows to estimate non-communicable disease prevalence (cardiovascular disease, cancer, diabetes) via pharmaceutical metabolites in wastewater. By quantifying 82 drugs and metabolites, they validated wastewater-derived estimates against prescription data, showing WBES's utility for chronic disease monitoring. A separate review (Amin et al., 2023) supported WBES's role in cardiovascular and cancer monitoring using urinary biomarkers. Duan et al. (2022) surveyed 168 pharmaceuticals and metabolites in Beijing wastewater, observing temporal variations linked to holidays and lifestyle changes. Such monitoring can inform drug consumption patterns and detect improper pharmaceutical disposal. Estevez-Danta et al. (2024) also applied WBES to assess exposure to endocrine-disrupting bisphenols.

Applications and case studies

Multiple studies validated WBES for SARS-CoV-2 monitoring. Bayesian smoothing approaches improved short-term trend detection and outlier identification (Manuel et al., 2024). National and regional studies (Miyazawa et al., 2024 in Japan; Walker et al., 2024 in England) showed WBE-derived reproduction numbers tracked with clinical cases. Rector et al. (2024) confirmed comparability of respiratory virus detection in wastewater with clinical samples in Belgium. Shrestha et al. (2024) estimated norovirus infections in Japan via wastewater concentrations, confirming WBES's applicability to enteric diseases. Walker et al. (2024) piloted similar norovirus surveillance in England. Tiwari et al. (2022) provided a systematic review of WBES for antibiotic-resistant pathogens. They concluded WBE can complement hospital-based AMR surveillance but requires harmonisation of sampling and analytical methods. Rossi et al. (2023) demonstrated wastewater detection of *Candida auris* during a healthcare outbreak in Nevada, USA. This shows potential for fungal pathogen monitoring, which is traditionally underexplored.

Global surveillance networks

Li et al. (2023) proposed a global aircraft-based WBE network for pandemic early warning, leveraging airline hubs as sentinel nodes. Jin et al. (2024) similarly discussed wastewater surveillance through international airports.

Ethical, social and governance dimensions

Arefin et al. (2025) argued for embedding social justice principles into WBE. They highlighted risks of stigmatisation, inequitable data use, and lack of representation. Drawing on Nancy Fraser's framework, they proposed integrating economic, cultural, and political justice into WBE programme design. Cohen et al. (2024) examined challenges of implementing WBE in rural areas with limited sewerage infrastructure. They proposed tailored strategies, training programmes, and ethical safeguards to protect privacy and ensure benefits reach underserved populations. Ram et al. (2023) reviewed the ethical and legal dimensions of WBE, emphasising privacy, consent, and data governance. Transparency and community engagement are critical to maintain trust.

Data models and visualisation

Therrien et al. (2024) introduced a comprehensive open-source data model for WBE, enabling integration of heterogeneous datasets (e.g. viral loads, socio-economic indicators, geospatial data). This enhances interoperability and reproducibility. Interactive dashboards have been widely adopted for real-time WBES reporting. However, accessibility and interpretability remain uneven, particularly in marginalised communities. Addressing these gaps is vital for equitable impact.

Recommendations

- **Standardisation and harmonisation**: Given that diverse methodologies exist for each stage of the surveillance process, ranging from various sequencing technologies (such as shotgun metagenomics and targeted amplicon sequencing) to specific concentration and detection protocols, it is desirable to establish clear guidelines for each methodological category outlining how to effectively assure data quality.
- **Ethical and governance framework:** Embed principles of social justice, transparency, and community engagement into WBES programs. Establish clear protocols for data privacy and consent.
- **Infrastructure and capacity building:** Invest in wastewater monitoring infrastructure, particularly in rural and underserved areas. Provide training for local personnel to ensure sustainable implementation. Even in regions with limited or absent sewerage infrastructure, it is possible to identify hotspots through site-specific or facility-level monitoring. By strategically utilising low-frequency sampling to manage costs, authorities can still enable targeted interventions, such as prioritising additional testing or vaccination efforts, and achieve early prediction of infectious outbreaks.
- **Integration with public health systems:** Link WBES data with clinical and environmental health databases to create comprehensive surveillance networks.
- **Research and innovation:** Support studies on new biomarkers, detection technologies, and predictive modeling to expand WBES applications beyond infectious diseases.
- **Global collaboration:** Foster international partnerships for pandemic preparedness through shared data platforms and coordinated surveillance efforts.

Conclusions

WBES has evolved from a niche research tool into a cornerstone of modern public health surveillance. Its capacity to deliver timely, population-wide insights makes it indispensable for managing infectious disease outbreaks and monitoring chronic health conditions. The COVID-19 pandemic underscored its value, demonstrating how wastewater data can complement clinical reporting and guide public health interventions.

Looking ahead, WBES offers opportunities to enhance global health security, improve equity in health monitoring, and support evidence-based policymaking. However, realising this potential requires addressing technical, ethical, and infrastructural challenges. Standardisation of methods, robust governance frameworks, and inclusive implementation strategies are critical to ensure WBES benefits all communities.

As technological innovations continue to refine detection and modeling capabilities, WBES is poised to become an integral component of integrated health surveillance systems. Its expansion into monitoring non-communicable diseases and pharmaceutical usage further underscores its versatility. By fostering collaboration among scientists, policymakers, and communities, WBES can help build resilient health systems capable of responding to current and future challenges.

References

Amarasiri, M., et al. Pathogens and disease vectors/hosts monitoring in aquatic environments: Potential of using eDNA/eRNA based approach. *Science of the Total Environment*, 796, 148810, 2021.

Amin, V., et al. Systematic scoping review evaluating the potential of wastewater-based epidemiology for monitoring cardiovascular disease and cancer. *Science of the Total Environment*, 858, 160103, 2023.

Ando, H. and Reynolds, K. A., Wastewater-based effective reproduction number and prediction under the absence of shedding information. *Environmental International*, 194, 109128, 2024.

Ando, H., et al. Wastewater-based prediction of COVID-19 cases using a highly sensitive SARS-CoV-2 RNA detection method combined with mathematical modeling. *Environment International*, 173, 107743, 2023.

Arefin, M. R. et al., Making waves: A justice-centered framework for wastewater-based public health surveillance. *Water Research*, 268. 122747, 2025.

Armenta-Castro, A. et al., Urine biomarkers for Alzheimer's disease: A new opportunity for wastewater-based epidemiology. *Environment International*, 184, 108462, 2024.

Ceolotto, N. et al., A new wastewater-based epidemiology workflow to estimate community wide non-communicable disease prevalence using pharmaceutical proxy data. *Journal of Hazardous Materials*, 461, 132645, 2024.

Cohen, A. et al., The benefits and challenges of responsibly implementing wastewater-based surveillance for rural communities. *Water Research*, 250, 121095, 2024.

Devianto, L. A. et al., Identification of protein biomarkers in wastewater linked to the incidence of COVID-19. *Science of the Total Environment*, 951, 175649, 2024.

Devianto, L. A. et al., Systematic review and meta-analysis of human health-related protein markers for realizing real-time wastewater-based epidemiology. *Science of the Total Environment*, 897, 165304, 2023.

Duan, L., et al. Wastewater surveillance for 168 pharmaceuticals and metabolites in WWTP: Occurrence, temporal variations and feasibility of metabolic biomarkers for intake estimation. *Water Research*, 216, 118312, 2022.

Estevez-Danta, A. et al., Wastewater-based epidemiology methodology to investigate human exposure to bisphenol A, bisphenol F and bisphenol S. *Water Research*, 261, 122016.

Jin, S. et al., Feasibility of wastewater-based detection of emergent pandemics through a global network of airports. *PLOS Global Public Health*, 4(3), e0003010, 2024.

John, A. et al., Assessing different next-generation sequencing technologies for wastewater-based epidemiology. *Water Research*, 267, 122465, 2024.

Li, J., et al. A global aircraft-based wastewater genomic surveillance network for early warning of future pandemic, *Lancet Global Health*, 11, e791-795, 2023.

Martinez-Puchol, S. et al., Characterization of the sewage virome: comparison of NGS tools and occurrence of significant pathogens. *Science of the Total Environment*, 713, 136604, 2020.

Manuel, D. G. et al., Wastewater-based surveillance of SARS-CoV-2: Short-term projection (forecasting), smoothing and outlier identification using Bayesian smoothing. *Science of the Total Environment*, 949, 174937, 2024.

Miyazawa, S. et al., Wastewater-based reproduction numbers and projections of COVID-19 cases in three areas in Japan, November 2021 to December 2022. *Eurosurveillance*, 29(8), pii=2300277, 2024.

Ram, N., et al. Ethical and legal wastewater surveillance. *Science*, 37 (6633), 2023.

Rector, A. et al., Respiratory viruses in wastewater compared with clinical samples, Leuven, Belgium. *Emerging Infectious Diseases,* 30(1), 141-145, 2024.

Rossi, A. et al. Candida auris discovery through community wastewater surveillance during healthcare outbreak, Nevada, USA, 2022, *Emerging Infectious Diseases*, 29(2), 422-425, 2023.

Shrestha, S. et al., Estimation of norovirus infections in Japan: An application of wastewater-based epidemiology for enteric disease assessment. *Science of the Total Environment*, 912, 169334, 2024.

Therrien, J. D. et al., A comprehensive, open-source data model for wastewater-based epidemiology. *Water Science and Technology*, 89(1), 1-19, 2024.

Tiwari, A., et al. Wastewater surveillance of antibiotic-resistant bacterial pathogens: A systematic review. *Frontiers in Microbiology*, 13, 977106, 2022.

Walker, D. A. et al., Piloting wastewater-based surveillance of norovirus in England. *Water Research*, 263, 122152, 2024.

| 3.8 |

Closing the loop: water sources, wastewater and water reuse: a present need and an ancient indigenous principle

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Introduction

Globally there is an increasing number of reports showing the presence of a higher number of emerging pollutants in the water sources (Mishra et al., 2023; US EPA 2025) and even in bottled drinking water (Akhbarizadeh et al., 2020) questioning suitability -notably for the future- of drinking water sources management and even of the conventional procedures to potabilise water. Concerning wastewater, the *de facto* reuse (Nguyen et al., 2018) is inviting the scientific community to reconceptualise the management of wastewater in order to incorporate water reuse for drinking purpose, either directly and indirectly as part of the management of water resources.

Key insights

Drinking water

The practice of discharging treated wastewater into rivers and surface water bodies is historical (UN-Habitat and WHO, 2021), even though they are also used as water sources. For several decades now, various authors have pointed out the drawbacks of this practice, as it leads to unplanned water reuse (Jiménez, 2011; Rice et al., 2013; Rice & Westerhoff, 2015; Swana et al., 2020). This *de facto* reuse, as it has come to be called, is one of the main reasons why there is an increasing number of synthetic contaminants. It is time to plan on moving from the *de facto* reuse to a fully planned reuse of water.

Sanitation

In countries and regions with temperate climates, the main disposal route for wastewater is surface water bodies. In contrast, in arid and semi-arid climates, wastewater is productively disposed of and used for agricultural irrigation (Zhang & Shen, 2017; Mishra et al., 2023). Under such conditions, discharge control parameters should aim to focus on the needs to productively reuse water. Unfortunately, it is common for Global South countries – where large volumes of polluted water are reused for irrigation – to indiscriminately copy Global North wastewater standards, resulting in regulations that do not address local health issues and are more costly and harder to achieve (Jiménez-Cisneros and Chavez-Mejía, 1997; Mara, 2003; Jiménez, 2007; WHO, 2006).

Wastewater treatment systems and associated policies have followed a historical development path. After wastewater collection, the need to prevent pump clogging and sediment accumulation in channels and tanks led to the use of screens, bar racks, and grit chambers – what is now known as pre-treatment in treatment plants. Later, to prevent fish kills in rivers and lakes – caused by wastewater discharges reducing dissolved oxygen – and to reduce diarrhoeal disease transmission from consuming contaminated water, processes for organic matter removal (biological processes) and disinfection were implemented (Metcalf & Eddy, 1991; Number Analytics, 2025; Mohammad et al., 2013; Milani & Bhendi, 2022; Zepon & Azapagic, 2023). Over time, as eutrophication problems became apparent, nutrient removal processes were introduced (Vollenweider, 1968; Sawyer, 1966; Festus et al., 2024; Yamashita and Yamamoto-Ikemoto, 2014).

Policies and regulatory frameworks follow this same logic referring in practice both to specific processes and treatment steps as if they were universal rules (notably thanks to the BAT (Best Available Technology), concept Brinkmann et al., 2016; Wikipedia 2025; OECD, 2022). But, in arid and semiarid countries, where several Global South countries are located and where water is frequently reused for agricultural irrigation rather than discharged into surface water bodies, they have the opportunity to implement more compact, and less expensive treatment schemes (Cisneros, 2011; Kines et al., 2021).

Case study: implementing reuse schemes in the Global North – the San Francisco example

To illustrate the need to implement reuse schemes and the challenge to face EP, a case from San Francisco has been chosen. This example also showcases de facto water reuse. San Francisco, California, became the first municipality in the USA to adopt a groundbreaking programme that encouraged buildings to collect, treat, and reuse water on-site to meet non-potable demands such as toilet flushing and irrigation. The programme was promoted by the San Francisco Public Utilities Commission (SFPUC). The San Francisco's On-site Water Reuse Program established a streamlined process allowing to alternate water sources, such as rainwater, stormwater, foundation drainage, greywater, and wastewater, to be reused in commercial, mixed-use and residential buildings. Implemented by four city departments, the On-site Water Reuse Program is a successful example of investing in collaboration and eliminating barriers to using water more efficiently and wisely managing both, water supply and sanitation services (Kehoe and Chang, 2018).

Recommendations

Topics for future research

- Alternatives to control emerging pollutants in water resources, including water treatment but also the prevention of their presence in water such as the production of green chemicals, a controlled use of compounds, etc.
- Coupling sanitation with water reuse to face lack of water and future impacts from climate change.
- Investigate the technical, social and economic barriers to upscale water reuse as a part of the water supply and sanitation services, considering different settings and context from Global South and Global North countries.

Policy needs

- Select water and wastewater management policies and regulation based on your local context, considering water reuse as an integral part of both practices.
- Set up specific policies to properly treat wastewater used for irrigation in regions where untreated or partially treated wastewater is used for food.
- Produce/refine advocacy, communication, education, and awareness raising programs to support the provision of sustainable and circular water services.
- Link the planning of future works to water reuse and resource recovery practices to make more affordable and better sanitation programmes.
- Where relevant, consider using not only westernised pollution control schemes but also indigenous communities' patterns (McGregor, 2014 & 2023; Wilson & Insker, 2018; Martinez-Cruz et al., 2024). Use these types of approaches as an alternative to the still westernised circular economy approach as they might provide new philosophies and solutions, notably when it comes to the reuse of water and the recovery of by-products (Vargas-Alarcón et al., 2007; Becerril & Jimenez, 2007; Klein, 1993; Anaya Rodríguez, 1992; Reyna Ortiz, 2015).

Conclusion

All over the world there is increasing evidence of pollution of water source with new pollutants because of human activity. Given the need to continue using the same water everywhere and throughout generations, it is important to manage water more wisely and in light of the hydrological cycle. Linking wastewater discharging norms to water quality use criteria is essential along with improving wastewater and drinking water treatment processes. There should also be programmes to prevent pollution caused by the use, production, and discharge of recalcitrant toxic compounds into the environment. Coming back to the indigenous principles in which all ecological cycles should be closed is becoming a must.

References

Akhbarizadeh, R., Dobaradaran, S., Schmidt, T.C., Nabipour, I. & Spitz, J., 2020. Worldwide bottled water occurrence of emerging contaminants: a review of the recent scientific literature. *Journal of Hazardous Materials*, 392, 122271. doi:10.1016/j.jhazmat.2020.122271.

Amin, M.M., Hashemi, H. and Bovini, A.M., 2013. A review on wastewater disinfection, *International Journal of Environmental Health Engineering*, 2(1), p.22. doi:10.4103/2277-9183.113209.

Anaya Rodríguez, E., 1992. *La Química del México Prehispánico*. Tesis de Licenciatura en Química, UNAM. [In Spanish]

Arman, et al., 2021. A review of emerging pollutants in the water environment: existences, health effects, and treatment processes. *Water*, 13, 3258.

Becerril, E. & Jiménez, B., 2007. Potable water and sanitation in Tenochtitlan Aztec culture. *Water Science and Technology*, 7(1), 147–154. doi:10.2166/ws.2007.017.

Brinkmann, T., Santonja, G.G., Yükseler, H., Roudier, S. & Delgado Sancho, L., 2016. Best available techniques (BAT) reference document for common waste water and waste gas treatment/management systems in the chemical sector. EUR 28112 EN. Luxembourg: Publications Office of the European Union. Available at: https://bureau-industrial-transformation.jrc.ec.europa.eu/sites/default/files/2019-11/CWW_Bref_2016_published.pdf

Cisneros, B.J., 2011. Safe sanitation in low economic development areas. In: Wilderer, P. (ed.) *Treatise on Water Science*. Vol. 4. Oxford: Academic Press, 147–201.

Jiménez-Cisneros, B. & Chávez-Mejía, A., 1997. Treatment of Mexico City wastewater for irrigation purposes. *Environmental Technology,* 18(7), 721–729. doi:10.1080/09593331808616590.

Jiménez, B., 2007. Helminth ova removal from wastewater for agriculture and aquaculture reuse, *Water Science and Technology*, 55, pp.485–493. doi:10.2166/wst.2007.046.

Jiménez, B., 2011. Safe sanitation in low economic development areas. In: Wilderer, P. (ed.) *Treatise on Water Science*, Vol. 4. Oxford: Academic Press, 147–201. doi:10.1016/B978-0-444-53199-5.00082-8.

Kathi, S. & Mahmoud, A.E.D., 2024. Trends in effective removal of emerging contaminants from wastewater: a comprehensive review. *Desalination and Water Treatment*, 317, 100258. doi:10.1016/j.dwt.2024.100258.

Kehoen P. and Chang T. 2018 Innovative water use in an urban setting. *Waterlines*, https://www.wateronline.com/doc/innovative-water-use-in-an-urban-setting-0001, Accessed December 2023.

Kines, K.J., Fox, M., Ndubuisi, M., Verocai, G.G., Cama, V. & Bradbury, R.S., 2021. Inactivating effects of common laboratory disinfectants, fixatives, and temperatures on the eggs of soil transmitted helminths. *Microbiology Spectrum,* 9(3), e0182821. doi:10.1128/Spectrum.01828-21.

Klein, C., 1993. Teocuitlatl, "Divine Excrement": The significance of "Holy Shit" in ancient Mexico. *Art Journal*, 52(2), 20–27. doi:10.2307/777364.

Kumar, R., Qureshi, M., Vishwakarma, D.K., Al-Ansari, N., Kuriqi, A., Elbeltagi, A. & Saraswat, A., 2022. A review on emerging water contaminants and the application of sustainable removal technologies. *Case Studies in Chemical and Environmental Engineering*, 6, 100219.

Mara, D., 2003. *Domestic wastewater treatment in developing countries*. London: Earthscan.

Martinez-Cruz, T.E., Adelman, L., Castañeda-Quintana, L. & Mejía-Montalvo, D., 2024. Water is more than a resource: Indigenous Peoples and the right to water. *Social Sciences & Humanities Open*, 10, 100978. doi:10.1016/j.ssaho.2024.100978.

McGregor, D., 2014. Traditional knowledge and water governance: the ethic of responsibility. *AlterNative: An International Journal of Indigenous Peoples*, 10(5), 493–507. doi:10.1177/11771801140100050.

Metcalf & Eddy Inc., Tchobanoglous, G. & Burton, F., 1991. Wastewater engineering: treatment, disposal and reuse. New York: McGraw-Hill Education. ISBN 0071008241.

Milani, S.A. & Bidhendi, G.N., 2022. A review on the potential of common disinfection processes for the removal of virus from wastewater. *International Journal of Environmental Research*, 16, 9. doi:10.1007/s41742-021-00387-.

Mishra, R.K., Mentha, S.S., Misra, Y., & Dwivedi, N., 2023. Emerging pollutants of severe environmental concern in water and wastewater: a comprehensive review on current developments and future research. *Water-Energy Nexus*, 6, 74–95.

Mishra, S., Kumar, R. & Kumar, M., 2023. Use of treated sewage or wastewater as an irrigation water for agricultural purposes – environmental, health, and economic impacts. *Total Environment Research Themes*, 6, 100051. doi:10.1016/j.totert.2023.100051.

Nguyen, T., Westerhoff, P., Furlong, E.T., Kolpin, D.W., Batt, A.L., Mash, H.E., Schenck, K.M., Boone, J.S., Rice, J.Y. & Glassmeyer, S.T., 2018. Modelled de facto reuse and contaminants of emerging concern in drinking water source waters. *Journal of the American Water Works Association*, 110(4), E2–E18. doi:10.1002/awwa.1052.

Number Analytics, 2025. Ultimate guide: chlorination wastewater engineering. Available at: https://www.numberanalytics.com/blog/ultimate-guide-chlorination-wastewater-engineering#:~:text=Introduction%20to%20Chlorination&text=The%20process%20involves%20the%20addition,the%20spread%20of%20waterborne%20diseases (Accessed: August 2025).

OECD, 2022. Best available techniques (BAT) for preventing and controlling industrial pollution: Value chain approaches to determining BAT for industrial installations. Paris: OECD Environment Directorate.

Reyna Ortiz, C., 2015. La materia fecal como indicador arqueológico en el estudio de la sociedad mexica. Tesis de Licenciatura en Arqueología, ENAH. [In Spanish]

Rice, J., Via, S.H. and Westerhoff, P., 2025. Extent and Impacts of Unplanned Wastewater Reuse in US Rivers. *Journal - American Water Works Association*, 107: E571-E581. https://doi.org/10.5942/jawwa.2015.107.0178

Rice, J., Wutich, A. and Westerhoff, P., 2013. Spatial and temporal variation in de facto wastewater reuse in drinking water systems across the USA, *Environmental Science & Technology*, 47(19), 11099–11105. doi:10.1021/es402792s.

Sawyer, Clair N. 1996. Basic concepts of eutrophication. Journal (*Water Pollution Control Federation*) 38 (5), 737–744

Swana, U., Feleni, U., Malefetse, T., Mamba, B., Schmitz, P. and Nkambule, T., 2020. 'The status and quantification of de facto water reuse in South Africa – a review', *Water Practice and Technology*, 15(2), 322–335. doi:10.2166/wpt.2020.021.

Tella, T.A, Festus, B., Olaoluwa, T.D., Oladapo, A.S. 2024. Water and wastewater treatment in developed and de.veloping countries: present experience and future plans. In: *Wastewater Treatment and Resource Recovery*. Elsevier, 351–385. doi:10.1016/B978-0-443-21794-4.00030-2.

UN-Habitat and WHO, 2021. Progress on wastewater treatment – global status and acceleration needs for SDG indicator 6.3.1. United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (WHO), Geneva.

United States Environmental Protection Agency (US EPA) (2025). Contaminants of emerging concern. Available at: https://www.epa.gov/wqc/contaminants-emerging-concern-including-pharmaceuticals-and-personal-care-products (Accessed: October 2025)

Vargas-Alarcón, G., Moscoso, J., Martinez-Laso, J., Rodriguez-Perez, J.M., Flores-Dominguez, C., Serrano-Vela, J.I., Moreno, A., Granados, J. and Arnaiz-Villena, A., 2007. 'Origin of Mexican Nahuas (Aztecs) according to HLA genes and their relationships with worldwide populations', *Molecular Immunology*, 44(5), pp. 747–755. doi:10.1016/j.molimm.2006.04.014.

Vollenweider, R.A., 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorous as Factors in Eutrophication. *Organization for Economic Co-Operation and Development*. Directorate for Scientific Affairs, Paris.

WHO, 2006. Guidelines for the safe Use of wastewater, excreta and greywater. Vol. 2: Wastewater use in agriculture. Geneva: World Health Organization. Available at: https://www.who.int/water_sanitation_health/publications/gsuweg2/en/

Wilson, N.J. and Inkster, J., 2018. 'Respecting water: Indigenous water governance, ontologies, and the politics of kinship on the ground', *Environment and Planning E: Nature and Space*, 1(4), pp. 516–538. doi:10.1177/2514848618789378.

Wikipedia, 2025. Best available technology. Available at: https://en.wikipedia.org/wiki/Best_available_technology (Accessed: October 2025).

Yamashita, T. and Yamamoto-Ikemoto, R., 2014. 'Nitrogen and phosphorus removal from wastewater treatment plant effluent via bacterial sulfate reduction in an anoxic bioreactor packed with wood and iron', *International Journal of Environmental Research and Public Health,* 11(9), pp. 9835–9853. doi:10.3390/ijerph110909835.

Zepon Tarpani, R.R. and Azapagic, A., 2023. 'Life cycle sustainability assessment of advanced treatment techniques for urban wastewater reuse and sewage sludge resource recovery', *Science of the Total Environment*, 869, 161771. doi:10.1016/j.scitotenv.2023.161771.

Zhang, Y. and Shen, Y., 2017. 'Wastewater irrigation: past, present, and future', WIREs Water, e1234. doi:10.1002/wat2.1234.

| 3.9 |

Water loss

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Introduction

Water loss reduction has become a central priority for water utilities worldwide as pressures on water resources intensify due to population growth, urbanisation, climate change, and rising energy costs. Water loss – commonly referred to as non-revenue water (NRW) – includes both physical losses from leaks, bursts, and overflows, and commercial losses arising from metering inaccuracies, data handling errors, and unauthorised consumption. In many regions, water losses account for 20–40 percent of system input volume, representing not only wasted water but also lost revenue, unnecessary energy use, and increased operational risk. As a result, reducing water loss is no longer viewed as a purely technical challenge but as a strategic imperative for sustainable water management.

Recent trends in water loss reduction reflect a shift from reactive, ad hoc approaches toward proactive, data-driven, and integrated management strategies. Traditionally, utilities relied on periodic leak surveys, customer complaints, and visible pipe failures to identify losses. While these methods remain relevant, they are increasingly supplemented – and in some cases replaced – by continuous monitoring technologies and advanced analytics. The widespread adoption of district metered areas (DMAs), smart meters, pressure sensors, and acoustic monitoring devices has enabled utilities to gain near-real-time visibility into network performance, allowing leaks to be detected earlier and repaired before they escalate into major failures.

Digitalisation is one of the most influential trends shaping modern water loss reduction programs. Advances in supervisory control and data acquisition (SCADA) systems, geographic information systems (GIS), and artificial intelligence (AI) have transformed how utilities collect, analyse, and act on data. Machine learning algorithms are now used to identify abnormal flow patterns, prioritise leak detection efforts, and predict pipe failures based on historical and environmental factors. These tools support more efficient allocation of resources and help utilities move toward predictive maintenance rather than reactive repair.

Another significant trend is the growing emphasis on pressure management as a cost-effective and sustainable means of reducing physical losses. By optimising pressure levels across distribution networks—often through the use of pressure reducing valves, advanced control systems, and real-time monitoring—utilities can substantially decrease leakage rates and extend asset life. This approach aligns water loss reduction with broader asset management and resilience objectives, recognising that controlling pressure not only saves water but also reduces the frequency of bursts and maintenance costs.

Institutional and regulatory developments are also influencing water loss reduction practices. Many regulators now require standardised water balance reporting, performance benchmarking, and long-term NRW reduction plans. This has encouraged utilities to adopt international best practices, such as those promoted by the International Water Association (IWA), and to integrate water loss reduction into corporate planning and governance frameworks. At the same time, there is increasing recognition of the human and organisational dimensions of water loss management, including staff capacity building, cross-departmental collaboration, and stakeholder engagement.

In summary, trends in water loss reduction point toward a more holistic, technology-enabled, and strategically aligned approach. By combining advanced monitoring tools, data analytics, pressure management, and strong institutional frameworks, utilities are better equipped than ever to reduce losses, improve service reliability, and ensure the long-term sustainability of water supply systems.

Trends in water loss reduction

The digital world is changing very fast. Only a few years ago, tools like ChatGPT and affordable Cloud computing were not widely available. Today, both hardware and software become obsolete quickly, and spare parts or support may disappear from the market in just a few years. This creates a real challenge for water utilities: how can you develop a long-term digital strategy when you cannot predict which technologies will exist in 5 or 10 years?

Given the speed of change, the goal for utilities is probably not to guess the "perfect" technology of the future, but to prepare a flexible foundation (IWA, 2022), which includes:

- investing in good data quality and clear data standards
- choosing systems that can connect through open interfaces (APIs)
- preferring modular and scalable Cloud-friendly solutions.

With this type of approach, the utility can gradually adopt new tools, replace old ones, and extend DMS capabilities over time—without starting from zero at each technological change.

Some modern trends that influence data management in water utilities are now presented:

1. PERFORMANCE BASE CONTRACTS (PBC)

More and more water utilities, especially in emerging and developing countries, are trying to move towards performance-based arrangements with their subcontractors as a measure of encouragement, efficiency and risk sharing (with mixed results so far, but new models are evolving) (S. Hamilton, 2024). In this context, PBCs have become an attractive option, where specialised private firm is engaged to manage and reduce water loss, with payment linked to target results such as lowering physical and commercial losses or increasing billed revenue. When well designed and implemented, PBCs generally achieve faster reductions in water loss from a wide range of starting conditions than conventional, utility-led projects (World Bank, 2023).

2. PUBLIC PRIVATE PARTNERSHIPS (PPP)

PPPs are repeatedly common long-term contractual arrangements in which public water utility work together with private operator to provide public services or develop infrastructure. In the water sector, these partnerships may be structured as management contracts, concessions, or joint ventures. By allocating risks and responsibilities between the parties, PPPs aim to improve operational efficiency and support investment in infrastructure and service delivery (OECD, 2025).

3. INCREASED QUALITY AND QUANTITY OF DATA

Very few water utilities today operate without some form of field measurement and historical data. Many now hold records spanning decades, opening new opportunities for operational optimisation and evidence-based decision-making. The rapid rollout of sensors, internet of things (IoT) devices, and smart meters is creating continuous streams of higher-quality, higher-frequency data across networks, treatment plants and customer connections.

4. SMARTER FIELD EQUIPMENT

With advances of nanotechnologies, each piece of modern field equipment can be a mini computer in itself with built-in communication: examples include smart meters analysing consumption and sending signals about anomalies, permanent leak detectors correlating noises to pinpoint the leak locations, actuators of control valves predicting DMA flow and adjusting the valve setting accordingly.

5. ADVANCED LEAK DETECTION METHODS

Innovative leak detection trends are moving toward wide-area screening, continuous monitoring, and data fusion rather than single, stand-alone techniques. Utilities increasingly combine satellite or airborne remote sensing to identify priority zones, fibre-optic sensing and high-resolution acoustic or pressure monitoring for continuous detection on critical assets, and advanced analytics such as transient analysis, smart meter data, and digital twins to narrow leak locations and estimate severity. The key shift is the integration of multiple data sources – flow, pressure, acoustics, AMI, and models – using AI to rank leak likelihood and guide field crews, improving speed, accuracy, and cost-effectiveness compared to traditional reactive surveys.

6. OPEN NETWORKS

Compared to the traditional approach to managing leaks and operating the water supply network by dividing it into isolated DMAs, new methods are increasingly used for leak detection in open networks. Especially, this is useful when the network is very difficult to divide into fully isolated sectors – for example, in dense and highly looped urban grids or in long branched tree-like rural networks – strict physical DMAs may not be practical. Many of these tools use AI-based methods to analyse large and complex datasets (flows, pressures, meter readings, detected leaks) and to identify correlations between various characteristics of network and associated leakage levels and locations.

7. DIGITAL TWINS

Building a computer representation of the water system to test "what-if" scenarios is a fast-moving field. A digital twin may be based on a traditional hydraulic model linked to SCADA data, or on data-driven predictive models using machine learning.

8. IMAGE RECOGNITION

Recent advances in computer vision allow extraction of information from images and video. Examples include automatic reading of analogue meters, detecting leaks from CCTV, drone or satellite footage, assessing asset condition from inspection images, and classifying documents based on scanned forms or drawings.

9. CARBON EMISSION LEAKAGE

The new IWA Water Loss Specialist Group (WLSG) initiative started the Leakage Emissions Initiative (LEI) to incentivise utilities to aggressively identify and reduce leakage, generating carbon credits which can then be sold to organisations seeking to achieve carbon neutrality (IWA Water Loss Specialist Group White Paper: Leakage Emissions Initiative. IWA, 2023). The idea is based on the fact that every unit of water lost to leakage results in carbon emissions that would otherwise be avoided if such leakage were reduced.

10. INCREASING WATER USAGE BY DATA CENTRES

Most modern data centres rely on water-based cooling systems, and global water demand from this sector is expected to roughly double by 2030. As a result, many water utilities are beginning to explicitly account for the water requirements of existing and planned data centres within their long-term strategic and investment planning, particularly in relation to source capacity, treatment, and peak demand management.

From another side, water conservation initiatives are starting to look beyond households and industry and include the "hidden" water footprint of digital activity. Some awareness and sustainability programmes are beginning to treat online behaviour as a demand driver: reducing unnecessary high-data activities (AI tools, cloud storage, video streaming, and other data-heavy services) is a practical water-saving action, especially in water-stressed regions (Smarter, Smaller, Stronger: Resource-Efficient Generative AI & the Future of Digital Transformation, UNESCO, 2025).

11. DIGITAL ROADMAPS

Recognising that digitalisation is inevitable, utilities are shifting away from buying isolated tools on an ad-hoc basis, and instead are developing structured digital strategies and roadmaps that link data initiatives directly to business objectives, investment plans and organisational change.

12. MOVING FROM EXCEL SPREADSHEETS TO APPS

The rise of no-code tools ("vibe coding") allows engineers and planners to build simple web and mobile applications, workflows, and dashboards without being expert programmers. Many tasks that were once handled in Excel are now implemented as shared apps and BI dashboards.

13. CHEAPER AND MORE ACCESSIBLE COMPUTATIONAL POWER AND STORAGE

Cloud-based analytics engines and storage services make it possible for even small and medium utilities to run complex simulations, store large volumes of time-series data, and use advanced analytics without investing in expensive on-premise servers.

14. AI EVERYWHERE

Artificial intelligence (AI) is increasingly present across all water utility processes. AI is particularly strong at coding, repetitive, pattern-based tasks, and handling large volumes of data. Its main value is to amplify engineers' expertise and help them do more with existing data. AI is already being used to predict leaks and equipment failures, optimise pressures and pump operation, and forecast water demand.

15. SAAS LICENSING

Traditional perpetual (permanent) software licenses are increasingly rare. Providers of data management systems now insist on Software as a Service (SaaS) models, where utilities pay recurring fees for access, updates, and support. This provides more predictable revenue for vendors and ensures continuous improvement of the software. More advanced, though still less common, models such as Data as a Service (DaaS) are emerging as an option to outsource the entire data handling process to a specialised contractor and allows utility personnel to focus on network operations

16. MOVING TO THE CLOUD

With growing needs for data processing and storage, it is becoming difficult for utilities to match these requirements using only their own physical infrastructure. As a result, the majority of modern platforms and applications are Cloud-based or hybrid. Although, the main constraint to using those powerful Cloud-based facilities is local regulation, which often prohibits storing sensitive information (such as customers' names and addresses) outside the country. This challenge is well known across many industries and can be overcome by using data centres physically located within the country or adopting hybrid architectures where sensitive data remains on-premise.

17. CORPORATE COPILOTS

Thanks to advances in automatic analysis of unstructured data (images, PDFs, reports, graphs, free-text notes), an entire utility's document archive can now be treated as a shared knowledge base or "data lake". Virtual assistants or "copilots" can query this information in natural language and retrieve relevant documents, data points, and past decisions, giving staff faster access to the organisation's collective memory.

18. CORPORATE AI AGENTS

If traditional AI model have for a long time been used for predictions, and more recent generative AI as "copilots", now there is the third generation of agentic AI which can act as serve as utility agents (Digital Water: GenAI and AgenticAI for Water Utilities, IWA, 2025). It could, for example, via telecontrols automatically adjust live PRV settings according to the current network conditions and pre-defined criteria: ensuring minimum required pressure for service while actively minimising leakage in a DMA.

19. INTEGRATION OF EVERYTHING

Whereas water utility departments once operated in silos using separate tools and datasets, modern technologies allow systems to "talk to each other" through APIs and standardised data models. The dream of many utilities is a single, integrated "brain" that connects customer information, commercial data, network operations, hydraulics, compliance, and asset management. Progress in this direction relies on strong interoperability, common key performance indicator (KPI) definitions, metadata standards, and data quality rules.

20. UNIFIED DATA AND ANALYTICS PLATFORMS

Looking ahead, one of the most promising directions is the development of unified data and analytics platforms (Eckerson, 2020). These platforms act as a "one-stop shop" for all data-related tasks of a utility. Instead of many disconnected tools, the utility can use a single environment where data is collected, stored, processed, analysed and visualised. Within such a platform, different "workloads" (or apps) handle different steps in the data chain:

- A data factory pulls raw data from sensors, loggers, SCADA and IoT devices
- Data engineering tools clean, validate, and combine data from different sources
- Data science tools build predictive models (for example, to forecast demand or detect leaks)
- A data warehouse stores historical data and trends in an organised way
- Real-time analytics modules monitor live performance indicators
- Reporting tools create interactive dashboards and standard reports for different users
- All these components store and access information from a shared data lake, usually hosted in the Cloud.

21. IT SMALLER START-UPS ENTERING WATER INDUSTRY

Smaller, agile companies focus primarily on software-driven analytics and they fill the growing gap between water and IT engineers. These firms, typically composed of 10–30 specialists, excel in data science, artificial intelligence, and customised software solutions. Their ability to quickly adapt and innovate gives them an edge in developing tailored, cutting-edge analytics tools. However, start-ups often operate with limited financial backing, meaning they may either be acquired by larger companies or face funding challenges. This introduces a level of uncertainty regarding their long-term availability and support.

22. GENERATIONAL GAP

The water and construction industries are traditionally conservative with long project cycles, outdated software, and one of the most aged workforces (Foundation for Water Research, 2023) and "silver tsunami" is quickly approaching. Younger professionals – native to the digital world – are entering the sector equipped with no-code platforms, Power BI dashboards, and chatbot assistants. Yet, water utilities have to find the way to attract those young engineers by "speaking" their language: flexible working schedule to accommodate work–life balance and family leaves (including paternity and maternity), possibility of remote work, competent salaries, and benefits. The good news is that water utilities perfectly match a growing trend among younger people to choose meaningful job and serve the local community.

23. NEW ENGINEERING ROLES IN WATER UTILITIES

If hydraulic modellers and GIS engineers have become a basic necessity for every water utility, they can no longer cover all data processing and analysis needs. Increasingly, utilities are employing data engineers and data analysts on a permanent basis to manage data acquisition, storage, processing, analysis, and presentation.

24. DATA MANAGEMENT SYSTEMS (DMS) MARKET ON THE RISE

In recent years, the market for digital tools targeting non-revenue water management has expanded rapidly, with a new NRW digital tool popping up every week promising to solve all the headaches of water utilities from network management to commercial operations.

However, for most of these modern tools, there are still only a few full-scale implementation examples (Torfs E. et al., 2022). Many success stories are based on isolated pilot projects rather than utility-wide adoption. According to the Gartner Hype Cycle for Emerging Technologies (Figure 3.17), NRW related DMS are probably at the Peak of Inflated Expectations where expectations are very high, but long-term, proven results remain limited:

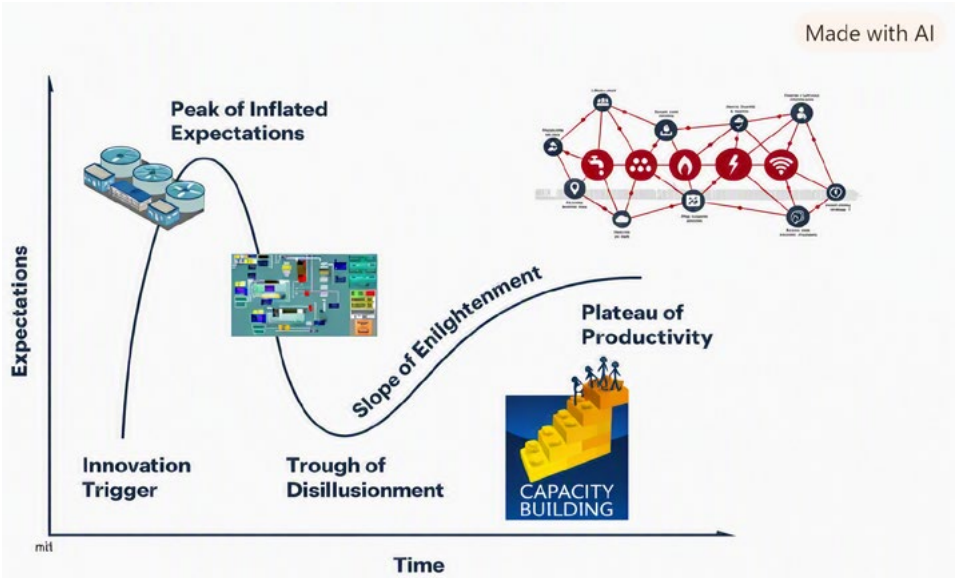


Figure 3.17: Gartner Hype Cycle for Emerging Technologies: AI in Water Industry. (Source: Newhart, K. 2023)

References

International Water Association (IWA). 2023. IWA Water Loss Specialist Group White Paper: Leakage Emissions Initiative. Available online at the IWA website.

International Water Association (IWA). 2025. Digital Water: GenAI and AgenticAI for Water Utilities.

S&P Global. 2025. Beneath the surface: Water stress in data centers.

AI in the Water Industry. (2023). CwMAG Workshop, November 2023. Tridend Group Solutions.

Cahn, A. and Mertzanis, M. (2024). *DaaS Playbook: It's All About Services*. SWAN, UK.

Digital Transformation for Growing Water Utilities. (2025). Boston Consulting Group (BCG) and Japan International Cooperation Agency (JICA).

Eckerson, W. (2020). *The Rise of Unified Data and Analytics Platforms*. Eckerson Group / Datalere.

EPA Interagency Water Workforce Workgroup. (2020). *America's Water Sector Workforce: Report to Congress*. U.S. Environmental Protection Agency, Washington DC, USA. Available at: https://www.epa.gov/sites/default/files/2020-04/documents/epa_water_workforce_report_to_congress_2020.pdf (accessed November 2025).

Féry, G. (2022). *The Digital Journey of Water and Sanitation Utilities in Latin America and the Caribbean: What Is at Stake and How to Begin*. Inter-American Development Bank (IDB), Washington DC, USA.

Foundation for Water Research. (2023). *Bridging the skills gap in the water sector.* Available at: https://www.fwr.org/water-sector-skills-gap (accessed 16 June 2025).

Grigg, N. S. (2025). Digital transformation in water utilities: status, challenges, and prospects. *Smart Cities*, 8(3), 99.

GSMA. (2022). *Water Utility Digitalisation in Low- and Middle-Income Countries: Experiences from the Kenyan Water Sector.* GSMA, UK.

Hamilton, S., Charalambous, B., Dalton, J., & Komy, N. (n.d.). Experiences from Performance-Based Non-Revenue Water (NRW) Reduction Contracts. Global NRW (white paper / guidance note). 2024. Available via: Global NRW resources hub.

International Water Association (IWA). (2022). *Digital Water Book 2022 – Digital Water White Papers Series*. IWA Digital Water Programme.

Mahajan, P. and Dhanasekar, A. (2025). Bridging the gap: bringing agile innovation to the water sector. *Water Online*, 8 May 2025.

Martinez Alzamora, F., Conejos, P., Castro-Gama, M. and Vertommen, I. (2021). *Digital Twins – A New Paradigm for Water Supply and Distribution Networks*.

Organisation for Economic Co-operation and Development (2025). Revisiting Public-Private Partnerships (PPPs) for water and sanitation: balancing risks, focusing on results. Background note.

Pérez Penalosa, F., Lombana, C. and Saltiel, G. (2024). *Utility of the Future 4.0.* International Bank for Reconstruction and Development / The World Bank.

Plumlee, M., Newhart, K. and Thompson, K. (2023). *Webinar: Artificial Intelligence (AI) in the Water Industry.* Orange County Water District. Available at: www.youtube.com/watch?v=M3AQTs5iN5g

PUB, Singapore's National Water Agency. (2020). *Digitalising Water – Sharing Singapore's Experience*. IWA Publishing.

Sarni, W., Sheehan, J. and Cox, T. (2023). *The Digital Journey of Water and Sanitation Utilities in the Caribbean*. Inter-American Development Bank (IDB), Washington DC, USA.

Torfs, E. et al. (2022). The transition of WRRF models to digital twin applications. *Water Science and Technology*, May 2022.

World Bank. (2025). *Digital Transformation Overview*.

World Bank. (2024). *Water and Sanitation PPP*.

World Bank (2023). Performance-based contracts offer a pathway to efficient water management. World Bank Blogs – Public-Private Partnerships. Available at: https://blogs.worldbank.org/en/ppps/performance-based-contracts-offer-a-pathway-to-efficient-water-

UNESCO. 2025. Smarter, Smaller, Stronger: Resource-Efficient Generative AI & the Future of Digital Transformation. UNESCO, Paris. CI/DIT/2025/ER/01 Rev.



| 4 |

Circular economy and sustainable water management

| 4.1 |

Nutrient removal and recovery: circular economy and sustainable water quality management

Authors: *Kristian Sahlstedt, Tanja Rauch-Williams, Liu Ye, Rui Du, Nerea Uri Carreno, and Jacek Mąkinia on behalf of the Nutrient Removal and Recovery Specialist Group*

Purpose and scope

The purpose of this chapter is to provide an overview of the state-of-the-art of nutrient removal and recovery methods, their current directions of development, drivers and restrictions; highlight case studies from different countries; and conclusions and recommendations for further actions.

Introduction

General

Emissions of phosphorus (P) and nitrogen (N) from urban wastewater treatment plants (WWTPs) induce a burden on receiving water bodies, contributing to eutrophication, oxygen depletion, and algal blooming. While freshwater resources are being depleted at a global scale, protecting water quality from nutrient pollution becomes even more critical.

At the same time, nutrients present in wastewater are increasingly seen as not only pollutants to be removed, but as resources to be recovered and reused. Production of synthetic fertilisers produces large amounts of greenhouse gas emissions and utilises finite natural resources. Recent geopolitical instability, energy-price volatility, and supply-chain disruptions have accelerated the awareness of risk associated with the dependency of global fertiliser supplies, thus calling for alternative sources for fertiliser production.

Both nutrient removal and recovery are closely linked to pursuing various United Nations Sustainable Development Goals (UN SDGs), including:

- Clean Water and Sanitation (SDG 6)
- Responsible Consumption and Production (SDG 12)
- Climate Action (SDG 13)
- Partnerships for the Goals (SDG 17).

Regulatory framework

Regulation continues to be the main external driver of nutrient removal, while explicit recovery obligations remain limited. In Europe, the recast Urban Wastewater Treatment Directive strengthens pressure for lower nutrient discharges from most WWTPs of PE >10 000 and energy-neutral operation at national level by 2045, while also emphasising resource recovery without yet imposing binding recovery targets[6]. Explicit P recovery requirements already exist in Germany and Switzerland. Local authorities may opt for stricter requirements for sensitive water bodies. Likewise, in China, Australia and the USA, national baselines are supplemented by stricter local standards in water-stressed and restoration-focused regions or otherwise highly sensitive receiving waters [2,3, 5,12,13]. Across regions, the direction is consistent: nutrient limits are becoming more site-specific and, in sensitive catchments, more stringent.

Key insights and emerging trends: nutrient removal

Phosphorus and nitrogen removal technologies

The field is moving from widespread baseline nutrient removal toward tighter polishing and more selective process intensification. For brevity, two regions are highlighted in this section: Europe and North America. In Europe, P limits around 1.0 mg/L and N limits around 10 mg/L or 70% removal were already established under the earlier Urban Wastewater Directive, but leading plants now operate at much lower levels. In Finland and Sweden, which rely on chemical precipitation, 0.25 mg/L total P is a common requirement for large plants and 0.1 mg/L is increasingly a design target. In Central and Western Europe, biological nutrient removal (BNR) with anaerobic zones in mainstream or sidestream, often complemented by minor chemical dosing and tertiary filtration, is established practice. Overall, the best plants achieve 2–5 mg/L total N.

In the USA, implementation of P and N removal continues based on the acceptable surface water quality nutrient standards set by the US Environmental Policy Agency. Depending on the sensitivity of the surface water, these standards can be less than 2 mg/L total N and less than 0.1 mg/L total P. The speed and method with which states integrate these standards as limits in individual discharge permits for treatment facilities varies. Each year more plants adopt traditional BNR configurations and more recent innovative intensification processes, including side-stream enhanced biological P removal (S2EBPR), low dissolved oxygen BNR, sidestream and mainstream anammox, partial denitrification/anammox (PdNA), and membrane processes, such as membrane bioreactor (MBR) and membrane-aerated biofilm reactor (MABR).

Together, these patterns suggest that the technology base is mature, while the current differentiator is how fast regions translate tighter limits into plant upgrades.

Process intensification

Process intensification has moved from a niche research theme to a practical response to aging infrastructure, tighter permits, space constraints, and pressure to reduce both energy use and carbon emissions. The strongest near-term application is retrofit: increasing nutrient removal capacity within existing tankage rather than expanding footprints.

Several technology classes now have sufficient operating experience to be regarded as established options for intensification. For example, MABRs are being added to existing aeration tanks to lift nitrification and denitrification capacity while reducing aeration demand, with approximately 100 installations by 2026. Aerobic granular sludge (AGS) has likewise influenced a broader set of retrofit concepts focused on higher biomass retention and improved settling [4, 15].

Anammox has also progressed from sidestream success toward selected mainstream demonstrations. Recent work indicates that partial denitrification can provide a more controllable nitrite pathway than conventional shortcut routes, improving operational flexibility, and lowering aeration demand under some conditions. Special attention is moving globally towards BNR process stability and climate performance, in particular in BNR intensification and short-cut nitritation processes[9,10].

Overall, nutrient-removal intensification is no longer constrained by lack of candidate technologies. The stronger practical questions are plant-specific fit, capital and operational costs, operator capability, and whether performance gains can be achieved without increasing greenhouse-gas risk.

GHG emissions of nutrient removal processes

Among greenhouse gas (GHG) emissions, nitrous oxide (N_2O) is a critical consideration in modern nutrient removal because its global warming potential is nearly 300 times that of CO_2, and in some wastewater treatment plants it can dominate the operational carbon footprint[17]. The important shift in the field is that mitigation is increasingly actionable rather than merely diagnostic. Full-scale evidence shows that N_2O can be monitored and reduced using measures already available to utilities. The following factors can help mitigate emissions depending on the specific process conditions: longer sludge retention time, improved carbon and alkalinity dosing, aeration control, and load balancing, including step-feed configurations[10,16]. This makes GHG-aware process control part of the current state of good nutrient-removal practice rather than an optional add-on.

The global evidence base indicates plants that measure N_2O in real-time are better equipped to reduce N_2O emissions. The tools, sensors, models, and operational strategies are mature for widespread adoption.

Key insights and emerging trends: nutrient recovery

Phosphorus recovery

P recovery remains the most mature nutrient-recovery pathway in wastewater treatment, but its practical expression differs by sludge route and regional policy. In countries where sludge mono-incineration is common, especially Germany and Switzerland, recovery from ash has become a strategic development direction because regulation is pushing plants toward P recycling[6,7]. In regions where chemical polishing is widely used, recovery from chemically bound P in sludge is also gaining attention, including routes such as ViviMag (recovery as vivianite from sludge stream) and RAVITA (refining of sludge from polishing filtration). In North America, by contrast, the strongest business case has often been operational rather than regulatory: P-rich sidestreams from EBPR and anaerobic digestion create nuisance struvite, so intentional struvite crystallisation has been adopted to stabilise operations while also producing struvite or brushite as recovered fertiliser products.

Ash recovery, sidestream struvite recovery, and recovery as vivianite or from chemical sludge each correspond to different plant configurations and market conditions. Land application of biosolids still remains the dominant low-cost recycling route in much of Europe and North America, while a smaller number of utilities market higher-value products such as Milorganite (Milwaukee Metropolitan Sewerage District) and Bloom (DC Water). The status of the field is therefore one of partial maturity: several P pathways are proven, but uptake still depends strongly on local regulation, sludge handling practice, and product markets.

Nitrogen recovery

While a number of P recovery technologies are commercially available and in use, the situation with N recovery is different. Although the strategic rationale is strong because conventional ammonia production is fossil- and energy-intensive, commercial practice still relies mainly on indirect recovery, which is primarily achieved in practice by biosolids land application and struvite sequestration and harvesting. In struvite the yield for N recovery is significantly lower than for P. Technologies for N recovery can be grouped into biological (such as soil remediation products); chemical precipitation (e.g. struvite and vivianite), membrane distillation (MD), direct membrane filtration (DMF); stripping and adsorption; ion exchange (IE); and electro processes.

A market for recovered N products is emerging in industry, where many companies are seeking to improve their sustainability. This applies especially in pulp and paper industry (see case study for Finland). A growing market in agriculture can also be envisaged; however, a major leap in demand requires external support[1,8,14].

Case studies

Case study 1: struvite recovery in the USA – operational control as a route to product recovery

Early full-scale struvite recovery systems in the USA showed that P can be intentionally crystallised by means of EBPR and digestion sidestreams while at the same time reducing nuisance scaling and internal P recycling. Performance has not been uniform across all configurations, and some existing installations have subsequently discontinued operation. Even so, this remains one of the clearest examples of a recovery pathway that has moved into full scale operation because it solves an operational problem while also generating a usable product.

Case study 2: Finland – nutrient recovery becomes more credible when linked to existing industrial demand

Interest from the pulp-and-paper sector shows how demand-side conditions can improve the prospects of nutrient recovery. Companies seeking lower-carbon inputs are evaluating recycled N and P products as substitutes for conventional chemicals. Chemical sludge from tertiary treatment steps of WWTPs is among the studied alternatives to replace urea and phosphoric acid.

In Finland, the state-owned company Gasum produces various nutrient products in their biogas plants. Reject water is enriched to around 3000–4000 mgN/L, after which evaporation yields a concentrate with up to 2.5% N and 0.4% P, and a separate ammonia-water stream for industrial reuse as NOx removal from flue gases and in wastewater treatment of pulp and paper production. The case is valuable not because it closes the entire N cycle, but because it demonstrates a realistic configuration in which wastewater-derived nutrients can displace virgin products in specific applications.

Case study 3: China – mainstream PD/A and PN/A illustrate the movement from demonstration toward practice

Recent Chinese demonstrations are among the strongest current examples of mainstream anammox-related innovation at large scale. Reported systems integrating partial nitritation or partial denitrification with anammox have achieved stable operation over wide temperature ranges, including one full-scale configuration operating from 11.6 to 28.9 °C with average total N removal above 90%. These results support the view that mainstream shortcut N removal is moving beyond laboratory validation. At the same time, they should still be interpreted as evidence of significant progress rather than proof of universal transferability across plant types and climates.

Conclusions and recommendations

The evidence reviewed here indicates that nutrient removal remains the more mature and broadly deployable part of the field, while nutrient recovery continues to advance through a smaller number of configuration-specific pathways. For removal, the dominant trend is the combination of proven BNR platforms with polishing and retrofit intensification measures to meet lower residual nutrient limits under tighter energy and carbon constraints. For recovery, P pathways are already credible in several plant contexts, especially sidestream struvite systems and ash-based routes where policy and sludge handling support them. N recovery is progressing more slowly, with the strongest near-term prospects in cases where product quality, concentration, and logistics match an existing industrial or agricultural use[1,6,7,14].

Several barriers still limit broader implementation of nutrient recovery, particularly for N products. Improvements are still needed in product purity, concentration, handling, storage, and cost efficiency. Scaling up the use of recovery products as fertilisers also requires improved crop yields, supportive government incentives, clear regulatory frameworks, quality standards, and stronger confidence among end users regarding wastewater-originated fertilizer products[14]. The latter applies also to the direct land application of stabilised sludge products, which is by far the most cost-efficient method of nutrient recycling. Conversely, applications other than fertilising, such as supplementing process chemicals in industrial processes must be evaluated further. Cross-sector collaboration between water industry, other industries and agriculture should be promoted, e.g. through common marketplaces for recovered nutrient products.

References

1. Al-Juboori, R.A., Al-Shaeli, M., Aani, S.A., Johnson, D., Hilal, N., (2023). Membrane technologies for nitrogen Recovery from waste streams: scientometrics and technical analysis. *Membranes* 13, 15. https://doi.org/10.3390/membranes13010015.

2. Beijing EPB (2012). Discharge Standard of Water Pollutants for Municipal Wastewater Treatment Plants (DB11/890-2012). Beijing Municipal Ecology and Environment Bureau.

https://sthjj.beijing.gov.cn/bjhrb/resource/cms/article/bjhrb_810268/502337/2019122315153572044.pdf

3. CRC Centro Committee (2016). Opinion on the Comprehensive Implementation of the River Chief System. General Office of the CPC Central Committee and the General Office of the State Council.

http://www.gov.cn/zhengce/2016-12/11/content_5146668.htm

4. Ekholm, J., De Blois, M., Persson, F., Gustavsson, D. J. I., Bengtsson, S., Van Erp, T., & Wilén, B. (2023). Case study of aerobic granular sludge and activated sludge—Energy usage, footprint, and nutrient removal. *Water Environment Research*, 95(8), e10914. https://doi.org/10.1002/wer.10914

5. EPA Victoria (2021). Guidance for environmental and human health risk assessment of wastewater discharges to surface waters (Pub 1962). Environment Protection Authority Victoria.

https://www.epa.vic.gov.au/guidance-risk-assessment-wastewater-discharges-surface-waters

6. European Commission: https://eur-lex.europa.eu/eli/dir/2024/3019/oj

7. Hidalgo, D., Corona, F., Martín-Marroquín, J.M. (2021). Nutrient recycling: from waste to crop. *Biomass Conversion and Biorefinery*, 11, 207–217. https://doi.org/10.1007/s13399-019-00590-3

8. Uzkurt Kaljunen J., Al-Juboori, R.A., Mikola, A., Righetto, I. Konola, I. (2021). Newly developed membrane contactor-based N and P recovery process: pilot-scale field experiments and cost analysis. *Journal of Cleaner Production*, 281 125288, doi: 10.1016/j.jclepro.2020.125288.

9. Kuokkanen, A., Blomberg, K., Mikola, A., Heinonen, M. (2021). Unwanted mainstream nitritation-denitritation causing massive N_2O emissions in a continuous activated sludge process. *Water Science Technology*, 83 (9): 2207–2217. https://doi.org/10.2166/wst.2021.127

10. Lake, A., Vellacott, A., Ye, L. (2024). The challenges of eliminating nitrous oxide from the water sector: https://www.thechemicalengineer.com/features/the-challenges-of-eliminating-nitrous-oxide-from-the-water-sector/

11. MEE (2002). Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002). Ministry of Ecology and Environment of the People's Republic of China.

https://english.mee.gov.cn/Resources/standards/water_environment/Discharge_standard/200710/t20071024_111808.shtml

12. NSW EPA (2022). Licensing Guidelines: Sewerage Systems. NSW Environment Protection Authority. [Protection of the Environment Operations Act 1997]. https://www.google.com/search?q=https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/licensing/22p3981-guide-to-licensing.pdf

13. QLD DES (2019). Environmental Protection (Water and Wetland Biodiversity) Policy 2019. Queensland Department of Environment and Science. https://www.legislation.qld.gov.au/view/html/inforce/current/sl-2019-0156

14. Sniatala, B., Al-Hamzi, H., Sobotka, D., Zhai, J., Makinia, J. (2024). Advancing sustainable wastewater management. A comprehensive review of nutrient recovery products and their applications. *Science of the Total Environment*, 937, 173446. https://doi.org/10.1016/j.scitotenv.2024.173446

15. Uri-Carreño, N., Nielsen, P. H., Gernaey, K. V., & Flores-Alsina, X. (2021). Long-term operation assessment of a full-scale membrane-aerated biofilm reactor under Nordic conditions. *Science of the Total Environment*, 779, 146366. https://doi.org/10.1016/j.scitotenv.2021.146366

16. Watercare: Nitrous Oxide emissions reduction strategy. https://promising-sparkle-d7f0c0cfc9.media.strapiapp.com/nitrous_oxide_emissions_reduction_strategy_2024_e20349a160.pdf?utm_source=chatgpt.com

17. Ye, L., Porro, J., Nopens, I. (2022). *Quantification and Modelling of Fugitive Greenhouse Gas Emissions from Urban Water Systems*, IWA Publishing. https://doi.org/10.2166/9781789060461

| 4.2 |

Accelerating resource recovery in the water sector

Authors: *Ana Soares, Wen Zhen, Gustavo Possetti, on behalf of the IWA Resource Recovery Cluster*

Circular economy thinking is reshaping how the water sector defines sustainability and performance. The historical model – extract, treat, use, collect, treat, dispose – was built to protect public health and receiving waters. It has delivered enormous value, but it is increasingly misaligned with today's constraints and expectations: water scarcity and hydrological volatility; rising energy and chemicals costs; nutrient supply risks; tighter climate and carbon commitments; and growing demand for resilient services in locations with old infrastructure as well as fast-growing or underserved communities.

In response, a new systems logic is evolving water and wastewater as managed resource streams. This current shift reframes "potable water and wastewater infrastructure" into a platform for (1) reclaimed water, (2) energy and energy carriers, (3) nutrients and soil products, and (4) materials and chemicals – enabled by new process trains, governance models, and markets for recovered products. The IWA Resource Recovery from Water Cluster exists to accelerate this transition by connecting research and development, water industry practitioners, and end-users of recovered materials, while promoting approaches that are both economically and environmentally attractive.

Cluster growth and renewed direction

The Cluster's growth from 11 to 22 core members, and its refreshed four-pillar structure around communication, institutional strength, technical contributions, and start-up support, reflects a wider change in the field: resource recovery is moving from isolated technical innovation towards deployment ecosystems that require trust, legitimacy, practical guidance, and market readiness.

Alongside this growth, the Cluster co-Chairs Professor Ana Soares (Cranfield University, UK) and Dr. Gustavo Possetti (SANEPAR, Brazil) articulated a renewed vision and strategy designed to better "define, shape and influence" resource recovery in the sector through clearer communication, stronger institutional positioning, practical technical contributions, and targeted support to innovators and start-ups. The updated vision is supported by four pillars:

1. **Communication:** unify messaging across IWA communities, amplify visibility of resource recovery outcomes, and tell "authentic, human-centred" stories through improved web presence, short-form video, and interview-style content.
2. **Institutional strength:** enhancing partnerships (e.g. UNIDO, UN development bodies, Water Europe, European Water Council (EWA)), co-branded outputs, and participation in global advocacy moments aligned with SDGs.
3. **Technical contributions:** facilitate translation research and practical know-how via technical notes or guidance and contracted projects to accelerate adoption by utilities and end-users, potentially co-branded with partners to expand credibility and reach.
4. **Start-up support:** as a long term goal, the Cluster aims to create a visible pipeline of deployable solutions through maturity assessment approaches and light-touch validation that helps innovators build trust with utilities, customers, and investors.

This strategic refresh is timely. Circular economy in water is now less about "promising pilots" and more about enabling **repeatable**, **financeable**, **regulated**, **and trusted** models of deployment.

Key insights: global trends shaping circular economy and sustainable water management

Resource recovery is moving from "unit processes" to "value chains"

A defining trend is that successful resource recovery cannot be evaluated solely on treatment performance. It must be evaluated on whether recovered outputs function as **products** within real value chains: who uses them, under what standards, with what quality assurance, at what cost, and with what liability. This is why the resource recovery conversation increasingly emphasises end-of-waste definitions, certification pathways, and market design – not just reactor efficiencies.

This value-chain insight was a clear message from recent Resource Recovery Cluster discussions and the 6th IWA International Resource Recovery Conference in Leeuwarden in 2025, where attention shifted strongly towards product pathways, end-of-waste barriers, and the conditions needed for practical uptake.

"The lesson is consistent globally: technical feasibility is necessary, but it is rarely sufficient."

The Wetsus organisers (Dr Leon Korving and Dr Thomas Prot), with support from the Cluster and IWA, published the digital edition of the IWA Resource Recovery Conference 2025 magazine that captures insights, discussions, and inspiring ideas that shaped the IWA Resource Recovery Conference – it's well worth reading! (https://resourcesinwater.com)

Circularity is expanding beyond "water-energy-nutrients" into materials, chemicals, brines, and critical resources

Resource recovery portfolios are broadening. Nutrient recovery remains central, but circular water management increasingly includes recovery of materials and chemicals (e.g. extracellular polymeric substances and other bio-based products), brine and salt valorisation pathways, and recovery of metals and critical raw materials. This trend is visible in the thematic breadth of RR2025 sessions, which span nutrient recovery, water reuse, brine valorisation, and metal recovery – showing that "resource recovery" is now an umbrella for multiple interlinked circular pathways.

The strategic implication is important: circular economy projects become more resilient when they are designed for multiple outputs, reducing dependence on a single revenue stream or regulatory pathway. A facility that can combine reclaimed water sales/benefits, nutrient product pathways, and energy or materials recovery may be able to withstand market fluctuations better than a single-product approach.

Distributed and onsite systems are emerging as a serious complement to centralised infrastructure

While many resource recovery solutions are embedded in large wastewater treatment plants, a parallel global trend is the acceleration of distributed and onsite approaches, especially where sewer connections are absent, unaffordable, or too slow to deploy relative to need. These contexts include informal settlements, peri-urban expansion zones, rural communities, and public institutions like schools.

Distributed approaches become especially compelling under water scarcity, where local reuse directly offsets demand. Yet they also raise acute questions: governance, maintenance, monitoring, user trust, and responsibility for safe handling of recovered products. This is why the most promising distributed solutions are paired with service models that professionalise operations rather than leaving long-term performance to ad hoc community management.

Circular water management is increasingly framed as a climate and carbon strategy

Circularity is tightly bound to climate outcomes. Energy-intensive conventional treatment and nutrient removal pathways can carry significant operational emissions and greenhouse gas risks, while circular approaches can reduce emissions through energy recovery, reduced chemical inputs, avoided fertiliser production emissions, and reduced conveyance pumping. At the same time, circular designs must confront their own emissions profile (including methane and nitrous oxide risks), requiring careful system-level design and monitoring.

The Resource Recovery Cluster has explicitly highlighted the need to overcome "historical lock-in" and to rethink legacy paradigms, where they hinder energy efficiency and climate performance, emphasising new approaches to resource recovery and carbon management as part of the next transition in wastewater management.

Scaling depends on people and partnerships as much as technology

The circular economy in water is multi-disciplinary by nature. It requires technical expertise, but also procurement innovation, regulatory collaboration, financing capacity, and social acceptance work. RR2025 participation illustrates the multi-stakeholder character of the field, with hundreds of attendees and strong engagement from industry and young professionals, reinforcing that scaling circularity is as much about ecosystems and capacity as it is about inventions.

The Cluster's refreshed strategy acknowledges this reality directly through its pillars on communication, institutional partnerships, technical notes for practice, and start-up support—each designed to reduce friction between innovation and deployment.

Case study: IWA Resource Recovery Cluster Best Practice Award 2025

Winning initiative: "Resource Recovery from Wastewater: Onsite Reuse Through Water-Efficient Sanitation Systems (WESS) in Schools and Rural Communities" (WRC, South Africa). Award presented at the 6th IWA International Resource Recovery Conference, Leeuwarden, Netherlands (19–23 May 2025).

Why this case is a strong circular economy example

The objective of the Cluster's Best Practice Award is to raise awareness of practical solutions that recover resources from water and wastewater, providing alternative and economical resource sources and reducing water stress via circular approaches. The WRC case is compelling because it tackles circularity where it matters most for human development and resilience: sanitation services for schools and underserved communities, under water scarcity pressures.

The case exemplifies circular economy as a service transformation. Instead of treating sanitation as a linear disposal chain dependent on large networks, it treats sanitation as a distributed platform for water reuse and resource recovery – while maintaining the possibility of centralised professional service delivery.

Technology platform: Water-Efficient Sanitation Systems (WESS) and Non-Sewered Sanitation (NSS)

WRC's South African Sanitation Technology Enterprise Programme (SASTEP) accelerates adoption of WESS and NSS technologies, many originating from the "Re-invent the Toilet Challenge". These systems reduce water consumption by treating and reusing wastewater onsite and are implemented across schools, informal settlements, and communities. In doing so, they address water scarcity and create new value streams from human waste through water reuse and recovery of nutrients and energy.

A key conceptual insight is that WESS/NSS breaks dependence on central sewer networks. It replaces "centralised infrastructure + centralised treatment" with distributed infrastructure + centralised service. This matters because many regions cannot expand sewers and treatment plants quickly enough to meet demand, and because water scarcity increasingly makes onsite reuse valuable.

Demonstrated systems under SASTEP

The programme demonstrated multiple technology configurations, reflecting a modular, context-fit approach: (1) Clearwater WESS/NSS/RT – biological-membrane full recycle; effluent reused for flushing; (2) NEWgenerator WESS/NSS/RT – biological-electro-chemical full/partial recycle; effluent reused for flushing, nutrient-rich water for irrigation; biogas produced (not captured due to small quantities); (3) Aquonic WESS/NSS/RT – biological-biofilm full/partial recycle; effluent reused for flushing and sometimes irrigation; (iv) Dewdrop WESS/NSS/RT – nature-based biological treatment; effluent reused for flushing. Demonstrations also included low-flush / water-efficient toilet pedestals.

The portfolio approach is important. It shows that circular sanitation does not rely on a single "perfect" technology; it relies on selecting the right configuration for the site context, capacity, and reuse opportunities – while keeping service reliability and safety as the overriding constraints.

Centralised service models: the scaling engine

Distributed sanitation often fails at scale because operations and maintenance are underfunded, skills are insufficient, and responsibilities are unclear. The WESS case directly addresses this by developing and testing centralised service models that support local employment and reliable performance: **(1) Social franchising model**: a skilled technical service provider builds and standardises skills locally; the franchisor services technologies in communities; **(2) User-paid model (B2C)**: monthly fee covers CAPEX and OPEX; includes safe sludge removal and central treatment; **(3) Performance-based contract model:** aggregated and centralised services delivered by a qualified provider across distributed technologies and **(4) Multiple-use services and community-led models**: possible, but require strong community ownership and prerequisite skills.

This is a core circular economy insight: the circular system is the combination of technology + service delivery + product use pathway. Without service reliability, circularity collapses into risk.

Resource recovery potential: creating a portfolio of recovered products

The case identifies several potential recovered products: (1) treated blackwater recycled as flush water; (2) treated blackwater suitable for irrigation, with effluent used as liquid fertiliser; (3) yellow water used as liquid fertiliser or centralised for treatment (e.g. struvite reactor); (4) treated sludge for soil conditioning and (5) blackwater treatment processes generating biogas.

This portfolio illustrates circularity in practice: the system reduces freshwater demand, creates nutrient and soil amendment options, and offers energy recovery potential depending on scale and configuration. Importantly, the value of these outputs is context dependent – irrigation demand, fertiliser substitution potential, logistics, and safety standards shape what is feasible.

Commercialisation and enabling conditions: making circularity investable and credible

WESS success is described as the outcome of multi-stakeholder collaboration: government agencies, development banks, private sector partners, researchers, funders, and communities. WRC aligns stakeholders around a national vision, while SASTEP facilitates localisation and commercialisation through commercial partners.

Public sector adoption pathways are also critical: the National Department of Basic Education and municipalities deploy systems in schools and communities. Private sector partners manufacture, install, and operate systems—supporting local job creation—while the Department of Water and Sanitation supports integration into policies, norms, and standards.

A decisive enabling condition is standards alignment: the South African Bureau of Standards aligned ISO 30500 with a national standard (SANS 30500), enabling certification. This is a practical response to a global challenge: circular systems scale faster when they can be certified, financed, and regulated with clarity.

Equity and human outcomes: service quality as a circular economy dividend

The case highlights that modular, water-efficient, scalable systems allow deployment in underserved, water-scarce areas. By shifting from disposal to recovery, WESS offers a resilient and cost-effective approach aligned with circular economy principles and climate adaptation needs. Reported user acceptance is high, and schools hosting improved services reported reduced absenteeism – an example of how sanitation circularity can produce broader social benefits beyond "water metrics".

The rollout evidence underscores the scaling potential: SASTEP demonstrated WESS/NSS in 12 schools and three communities, followed by further adoption financed for 48 additional schools. Broader rollout is being supported by project preparation efforts designed to create bankable municipal and education-sector projects under a steering structure.

Recommendations from IWA Resource Recovery Cluster for the global water community

Drawing from the Cluster's strategic refresh and overall developments on this area, six practical recommendations emerge.

1. START CIRCULAR PROJECTS WITH A VALUE CHAIN MAP
Before selecting technology, define: the recovered product(s), target users, quality requirements, regulatory status, logistics, and revenue/benefit mechanism. RR2025's emphasis on value chains and end-of-waste navigation highlights how often these elements determine success.

Practical step: require every project concept note to include a one-page "product-to-market" pathway, even for public-sector reuse pathways (e.g. irrigation within school grounds).

2. TREAT STANDARDS, REGULATION, AND MONITORING AS DESIGN INPUTS – NOT AFTERTHOUGHTS
Recovered resources only create value if they can be trusted and legally used. The Cluster's renewed strategy explicitly prioritises institutional partnerships and third-party validation to strengthen credibility and influence.

Practical step: create joint working arrangements with regulators and standards bodies early, and co-develop monitoring plans, certification pathways, and responsibility matrices.

3. PAIR DISTRIBUTED TECHNOLOGIES WITH PROFESSIONALISED SERVICE MODELS

The WESS case shows that distributed systems can be scalable when professional service delivery is built in – through franchising, user-paid contracts, or performance-based aggregation. This is crucial for long-term safety and system integrity.

Practical step: shift procurement from "buy equipment" to "buy service performance," with clear KPIs on availability, effluent quality where reuse occurs, maintenance response times, and safe residual handling.

4. BUILD MULTI-OUTPUT PORTFOLIOS TO STRENGTHEN RESILIENCE AND ECONOMICS

Circular systems are more robust when they can generate multiple outputs (reused water, nutrients, energy, materials). RR2025's breadth of themes reinforces that the field is moving toward multi-stream recovery.

Practical step: incorporate multi-criteria analysis and life-cycle assessment to identify the best output portfolio for each context, rather than maximising a single recovery stream at the expense of overall system performance.

5. INVEST IN COMMUNICATION AND "TRANSLATION" CAPACITY

The Cluster's first pillar – communication – recognises that circular water management needs clear, consistent messaging and accessible stories to build public trust, political support, and practitioner uptake.

Practical step: develop a shared library of short case studies and technical explainers and reuse them across web, webinars, and partner channels, linking technical performance to real-world outcomes.

6. ACCELERATE ADOPTION THROUGH PRACTICAL GUIDANCE AND START-UP READINESS SUPPORT

The Cluster's vision includes a concise "Technical Notes Library" and structured start-up support to make innovations easier to adopt and to help innovators prove maturity and readiness.

Practical step: standardise "minimum information sets" for pilots and deployments (performance, costs, O&M requirements, risk controls, references) so utilities and municipalities can compare options and build bankable projects faster.

Conclusions

The circular economy and sustainable water management are increasingly a sector-wide necessity, not a niche ambition. The transition is technical, institutional, and social: it requires new process configurations, new product and quality frameworks, new contracting and service models, and new ways of telling the story of water systems as resource systems.

The IWA Resource Recovery from Water Cluster is adapting to this reality through measurable and a refreshed vision structured around communication, institutional strength, practical technical outputs, and start-up support.

Together, these pillars focus on what the circular transition now needs most: trust, legitimacy, and replicability.

The 2025 Best Practice Award case study from WRC in South Africa demonstrates circular economy in action where it is urgently needed – schools and underserved communities – through water-efficient sanitation systems that enable onsite treatment and reuse, nutrient and energy recovery opportunities, and scalable service delivery models. It shows how circular sanitation can deliver resilience under water scarcity, strengthen service quality, and generate broader social value.

For the global water community, the overarching lesson is that circular solutions scale when we engineer the full system: technology + service + standards + partnerships + user acceptance. With that integrated approach, circular economy principles can move from pioneering projects to routine practice – helping shape a future where water and sanitation systems are not only safe, but also resource-positive and climate-resilient.

| 4.3 |

Enhancing water treatment through advanced particle separation: water treatment of the future

Authors: *Arjen van Nieuwenhuijzen and Katsuki Kimura on behalf of the Specialist Group Particle Separation*

Introduction

Efficient particle separation (PS) remains a cornerstone of sustainable water treatment processes critical to achieving clean and safe water for all. The Specialist Group Particle Separation within the International Water Association (IWA) recognises the transformative potential of innovative particle separation technologies and strategies to address evolving global water challenges.

In the reporting period, the group's work reinforces key thematic areas prioritised by the Global Trends Report – especially regarding IWA-Theme 4 Circular economy and sustainable water management. This contribution summarises recent research, technological advances, and strategic approaches endorsed by the Specialist Group to guide policy makers, researchers, and industry stakeholders.

Foundational role of particle separation in water treatment and sustainable development

Particle separation processes underpin almost all conventional and advanced water treatment systems to remove suspended solids, pathogens, and contaminants that threaten human health and environmental integrity. These treatment stages are vital for drinking water production, wastewater treatment, and industrial effluent management, thereby safeguarding ecosystems and communities. Particle removal addresses multiple SDGs beyond SDG 6 especially SDG 12 (Responsible Consumption and Production) by enabling resource recovery.

Particle separation in relation to the circular economy and sustainable water management

Traditional particle separation processes generate sludge and waste streams posing environmental challenges. Aligning with SDG 12 (Responsible Consumption and Production), the Specialist Group promotes technologies that valorise separated particles as resources.

Innovations in advanced particle separation for removal of emerging substances from water and sludge create major opportunities for circular water reuse and resources recovery. New physical-chemical means of separation technologies improve residual treatment and enable recovery of nutrients, metals, and organic matter for reuse in industry and agriculture. Enhanced particle separation upstream reduces chemical loads and sludge volumes, improving the efficiency of downstream resource recovery stages.

Hybrid systems integrating membrane filtration with physical separators optimise solids capture and fractionation, producing higher-quality side streams amenable to circular reuse. An example of fresh water harvesting from sewers is shown in Figure 4.1.

Conclusions and outlooks

Conclusions

Advanced particle separation (APS) — encompassing separation, sortation and concentration — is a cornerstone technology for the water and wastewater treatment plant of the future. When correctly specified and integrated, advanced particle separation:

- Improves water quality and reduces loads to biological processes.
- Produces concentrated resource streams that are economically and technically suitable for recovery and valorisation.



The key finding of from the Sewer Water Harvesting Pilot for Urban Green Irrigation in Amsterdam, the Netherlands (by City of Amsterdam, W+B, WUR, AMS Institute, NXFiltration and Saur Nijhuis) was that water harvesting from sewer mains could be a future proof water source for urban green irrigation and other urban water users:

- *Direct fresh water harvesting from sewers by screening + filtering + hollow fiber direct nanofiltration is technical feasible;*
- *Water quality of the product water (permeate) is more than sufficient for irrigation of vulnerable urban green.*
- *Marco and micro pollutants were removed efficiently (see graphs below for waste water quality parameters and organic micro pollutants)*
- *Water harvesting could be a secure Fresh water sources for landscaping green, industrial and urban water supply in the future.*

Figure 4.1: Fresh water harvesting from sewers in Amsterdam, the Netherlands.

- Contributes materially to carbon-neutral and energy-efficient treatment pathways.
- Requires integrated design, digital control and enabling policy/business frameworks to achieve widescale adoption.

IT IS ADVISABLE TO:

- Incorporate advanced particle separations opportunities early in (waste)water treatment plant upgrade or new-build planning with clear mass-flow targets for recoverable fractions.
- Standardise pilot-scale testing protocols and performance indicators for APS technologies to enable comparative assessment and de-risking.
- Promote demonstration projects that couple APS with downstream recovery processes (phosphorus, organics-to-energy, materials recovery) and document whole-system lifecycle impacts.
- Develop regulatory and market measures that recognise and reward resource recovery and carbon reductions enabled by APS.

Outlooks

The Specialist Group Particle Separation's 2025–2026 contributions underscore the pivotal role of particle separation in advancing sustainable water treatment aligned with the UN Sustainable Development Goals. By fostering innovation, resilience, and inclusivity, the group supports IWA's vision of a water-secure world: www.iwaps2026.com/

The continued collaboration among researchers, practitioners, and policymakers will be essential to overcome remaining challenges and fully realise the benefits of particle separation science and technology in delivering safe, sustainable, and equitable water services worldwide.

In 2026 the Specialist Group Particle Separation Conference was held in June in Sapporo, Japan. This conference brought together experts, researchers, and industry professionals to explore the latest advances in particle separation technologies and processes across various industries, including water treatment, environmental protection, and materials processing, including a wide range of separation processes:

- Coagulation/ electrocoagulation and flocculation
- Media filtration
- Membrane filtration and membrane bioreactors
- Sedimentation and flotation
- Sludge handling

The conference focused also on emerging trends and technologies in particle separation, including:

- Removal and control of emerging contaminants
- AI and machine learning applications in separation processes
- Energy-efficient separation technologies
- Modelling and simulation
- Sustainable approaches using nature based raw materials
- Autonomous process control
- Hybrid and integrated processes
- Synergetic approaches in water and sludge treatment and resource recovery

References

A.F. van Nieuwenhuijzen (2026). The Importance of Advanced Particle Separation for the Wastewater Treatment Plant of the Future. Conference Proceedings IWA Particle Separation Specialist Group Conference 2026. www.iwaps2026.com/.

STOWA (2023). Waterfabriek 2.0: Naar toekomstbestendige en circulaire zuiveringsinstallaties. STOWA-2023-47. Available from: https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202023/STOWA-2023-47-Waterfabriek20.pdf

IWA (2024) Resource Recovery from Water. Available from: https://aquaminerals.com/wp-content/uploads/2024/08/Resource-Recovery-from-Water.pdf

VA-teknik Södra (2017). Advanced Particle Removal for Capturing the Value in Waste Water. Available from: https://va-tekniksodra.se/wp-content/uploads/2017/03/Advanced-Particle-Removal-for-Capturing-the-Value-in-Waste-water_final.pdf

IWA Next Generation Sanitation Systems (NGSS) Project (2025). Project outputs and guidance on integrated sanitation and resource recovery. (See IWA NGSS project webpages and publications for details.)

A.F. van Nieuwenhuijzen, et al (2023). Carbon neutral water production and resources recovery — the added value of advanced particle removal technologies for sustainable sewage water treatment. (IWA PS Conference Johannesburg, SA, November 2023).

| 4.4 |

Sustainability in the water sector

Authors: *Miriam Feilberg and Cheryl Davis on behalf of the Sustainability in the Water Sector Specialist Group*

Introduction

Setting a new agenda for sustainability

In 2026 we have only four years left to meet the SDGs. The sustainability agenda is not on track to meet the SDGs in general and for the SDG 6, and neither are we.

Our Sustainability Specialist group has organised a series of webinars to establish a new understanding of sustainability and demonstrate how to get sustainability into the heart of the water sector at strategic, management and operational level.

When we meet in Glasgow in October 2026, we will discuss how to promote organisational change to promote a strong focus on sustainability in the water sector.

Key terminology

SDGs: Sustainable Development Goals – an agenda for development adopted by UN in 2015 compromising 17 goals covering most social, environmental, and economic development issues. Sustainability relates to all three elements of our common activities, or people, planet and profit as it is sometimes referred to. The goals consist of 169 specific targets. The goals are to be met globally by 2030.

Sustainability: The understanding from the Brundtland report from 1987 is a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Absolute sustainability: Seeing nature's total tolerance limits as a measure of how much we can allow our products and actions to impact on the climate and the environment. Within this scope, we must all have food, clean water, shelter, transportation, etc.

Planetary boundaries: This framework identifies nine critical Earth system processes, defining a "safe operating space" for humanity by setting science-based limits on human impact to maintain stability and prevent potentially irreversible environmental changes.

Key insights

- We need an understanding of sustainability that includes absolute sustainability based on planetary boundaries to maintain a global safe operating space for our activities.
- Meeting the SDGs by 2030 means massive investments in water, wastewater, and climate adaptation structures, including building and transport. This comes with large carbon emissions, e.g. from concrete and transport of materials. We need to consider the emissions and find solutions that are less carbon intensive. Emissions such as from methane and nitrous oxide must also be looked at as they are significant emissions from wastewater transport and treatment.
- Nature-based solutions and non-sewered sanitation may be less carbon-intensive and we need to consider these on a larger scale.
- Strategic sustainability is important. Implementation of a strategy that is built around SDGs or other similar sustainability frameworks increases the uptake of sustainability and that actions are carried out in the whole organisation. To improve sustainability in the water sector it is necessary to include all levels of operation whether strategic or operational.
- Monitoring and reporting are important elements in sustainability. Building a strategy around sustainability and ensuring that you have robust monitoring and reporting systems around environment, social and governance matters (ESG-reporting) enable a better focus on carrying out sustainability in practice and following up or developing new sustainability measures where necessary.
- Sustainability is not just about environment. Governance, funding, and social elements are equally important. Diversity in the water sector is a key element which we discuss and include in all our activities.

- Among other important matters, the Specialist Group has been focusing on the role of women in the water sector. Since 2018, IWA's Specialist Group on Sustainability in the Water Sector has been actively involved in investigating the challenges faced by women in the water industry in their efforts to maximise their contribution to addressing water quantity, water quality, and climate change problems. Realising that the challenges faced by the water industry will require the full efforts and contributions of all members of the water industry, the Specialist Group decided to investigate challenges faced by women in the water industry, which has led to numerous activities around the topic.

Case study: webinars for working with sustainability

In the webinars we present examples of how working with sustainability at a strategic level will lead to more actions at the operational level. One case will be from Frederiksberg Utility in Denmark that demonstrates how the planetary boundaries and absolute sustainability perspective can be utilised at a utility and lead to actions on the ground.

Other cases from, for example, a water utility in the UK, Tampere Water in Finland, construction companies or consulting companies will demonstrate the use of different monitoring and reporting systems and how they will improve sustainability in the water sector and enable follow-up to ensure that actions are taking place, carbon emissions are lowered, social responsibility is improved, biodiversity is integrated in actions, etc.

Regarding women in water webinars, on-line workshops, and in-person workshops to obtain useful suggestions on how to move past the limitations of past practice have been held such as a webinar with Young Professionals; an on-line workshop in coordination with the African Water and Wastewater Association, an on-line workshop targeting the Middle East, and participation in the ICID conference in Thailand. Additional information-gathering events are planned for the Danube Region and Ecuador. Findings of these events will be analysed, documented, and presented at the IWA World Water Congress in Glasgow in 2026.

The cases will also be presented in detail in the Newsletter of the Specialist Group on Sustainability in the water sector and at events during World Water Congress and Exhibition in Glasgow in 2026.

Recommendations

Sustainability is under severe political pressure globally and at the same time it is urgent to speed up our actual actions to implement the SDGs and improve our sustainability impact globally and locally. New concepts such as planetary boundaries and absolute sustainability may help us better understand and improve our sustainability actions all over the water sector.

SDGs are still an important and valid framework for improving sustainability in the water sector. All organisations in the water sector must:

- Learn about the SDGs and where they matter for the organisation
- Develop a strategy for implementing the SDGs in their organisations
- Investigate their implementation gaps and develop actions to improve on these
- Monitor and report actions to improve sustainability based on different frameworks for ESG-monitoring.

Although unequal treatment of women in the water industry is an equity issue, it is not only an equity issue. The most significant issue is that the challenges facing the water industry are too deep and too serious to be adequately addressed unless we support and utilise the skills and talents of all members of the water industry.

Conclusion

In conclusion, the expected learning outcomes from our webinars and our activities in general are that:

- The water sector is contributing to several environmental pressures which are critical on a global level. The water sector plays a key role in order to meet the SDGs. SDG 6 in water, hygiene, and sanitation is of course very important, but also other SDGs like SDG 3 on Health and Well-being, SDG 11 on Sustainable Cities or SDG 14 on Life Below Water depend on the activities of the water sector for their implementation.

At the same time, we must not ignore the fact that the water sector also has a significant impact on the SDGs, not least SDG 13 on Climate Action. Our activities come with carbon emissions in treatment processes and from building and construction. We need to pay attention to our impact on the SDGs – both negative and positive.

- SDG 5: Achieve gender equality and empower all women and girls should still be in high focus in the water sector as our experiences demonstrate quite clearly. Diversity and inclusion of all in the water sector regardless of elements like gender and age is important to build a sustainable water sector and build an innovative water sectror for the future. We must address elements like career opportunities and advancement, the impact of disrespectful behavior and the need to build self-confidence. The importance of addressing work–life balance, mentoring and staff development; and the impact of age on challenges experienced must be taken into account.
- The planetary boundaries is a new element that can be used to move from “better” to “good enough”, ensuring a balanced and stable planet as the basis for human welfare.

The concept of planetary boundaries includes nine boundaries for the global environmental systems; seven of these have been exceeded by now. These are Climate Change, Biosphere Integrity, Land System Change, Freshwater Use, Biogeochemical Flows, Novel Entities, and Ocean Acidification and they show worsening trends from year to year. Only Ozone Depletion and Aerosol Loading remain in the safe zone. The planetary boundaries represent a safe operation space for all, including the water sector, and we must all find ways to keep our activities within the planetary boundaries that are universal in the same way as the SDGs.

- We must improve our strategic planning, monitoring and reporting to improve sustainability in the water sector.

Evidence from case studies show that integration of sustainability at all levels of the organisations contributes significantly to improving sustainability. It is important to start with integration of sustainability and elements like SDGs and planetary boundaries when developing the organisational strategy, but this is not enough and it needs to be followed by actions with the operations of utilities and companies. Monitoring and reporting of the activities are important to follow the development, see the results and adjust the actions if necessary.

These three elements are also areas where there is a need for further understanding and research to ensure that the water sector understands and contributes to meeting the global environmental and climate-related goals. In particular within the field of monitoring and reporting (sustainability reporting, ESG reporting), there is need for further research in reporting systems and tools and their relevance for utilities and other companies within the water sector.

| 4.5 |

Treatment of industrial waters: demands and challenges from emerging industry

Authors: *Yongjun Zhang, Sven Uwe Geissen, Henri Spanjers on behalf of the Specialist Group Treatment of Industrial Waters*

Introduction

Water is the most widely used raw material in industrial production which consumes roughly 15% of global water withdrawals, slightly higher than domestic use (13%)[i]. A higher share of industrial water consumption can be expected in industrialised regions than in developing regions. Conventional industries (textile, petro-chemical, pulp & paper) are well-known hotspots of chemical oxygen demand (COD), dyestuffs, heavy metals, and recalcitrant organics, which can be treated to meet discharge or reuse criteria with best available technologies consisting of separation, oxidation, biodegradation, etc., as discussed in following sections. However, the fastest growth in water consumption and discharge is now registered by emerging industrial sectors that may require ultra-pure or highly conditioned water and generate characteristic effluents with treatment technical challenges. For instance, bio-manufacturing (pharma, cultured meat, precision fermentation) needs bacteria-free, low-endotoxin water while releasing effluents with high COD, residual antibiotics and antifoams. Semiconductor production, as another example, used approximately 6.33× 108 m^3 water in 2022 globally, increased by 24.5% from 2019[ii], with the release of complex wastewater that contains HF, silica, and organic solvents. These examples illustrate a dual challenge: securing high water quality for emerging demand while treating increasingly complex, sometimes hypersaline, waste streams to a standard that allows internal reuse of water and materials to meet the requirements of the circular economy (Figure 4.2).

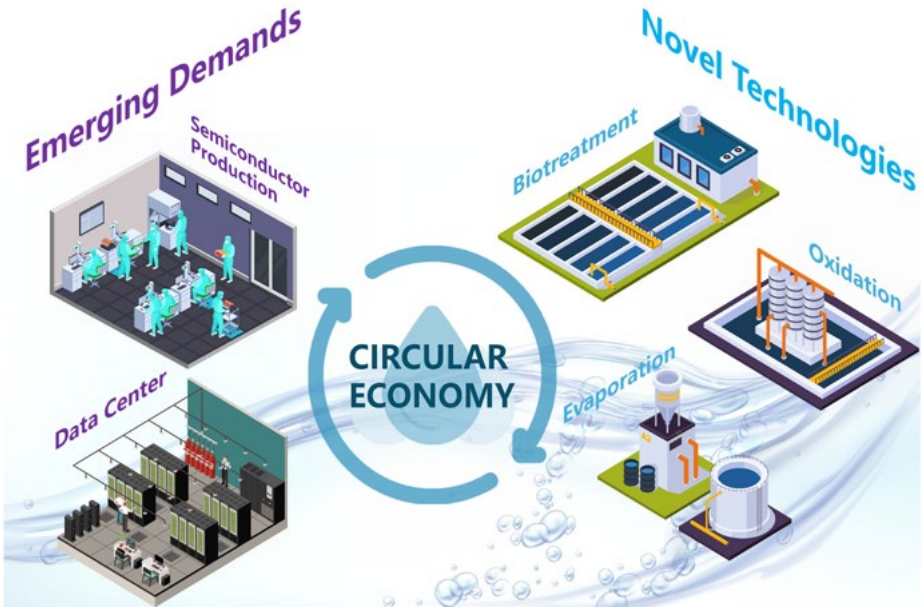


Figure 4.2: Emerging demands of extreme water quality waiting for novel treatment technologies.

Existing knowledge on treatment of industrial waters

To fulfil the water quality requirement of production processes or the reuse/discharging standards, treatment of industrial waters is generally based on (1) the destruction or elimination of contaminants, (2) the recovery of water and other resources, and (3) proper management of brine streams especially in the case of zero-liquid discharge. The following technologies are often applied.

Separation processes

Particles and other insoluble contents are conventionally separated with screening, sedimentation, dissolved-air flotation, and oil-water separation. Recently membrane filtration has moved from a tertiary add-on to the core of wastewater reuse train. Ultrafiltration membrane provides a reliable silt density index for downstream reverse osmosis. To reject multi-valent ions, particles, or agglomerates, nanofiltration can significantly reduce the energy input with low driving pressures about 0.5–1.0 MPa, several-fold lower than that of reverse osmosis[iii]. Nevertheless, fouling and scaling should be carefully managed for both nanofiltration and reverse osmosis with new membrane materials and properly pre-membrane treatment. Compared with conventional pressure-driven membranes, electrodialysis consisting of ion-selective membranes and an electric field can further elevate the water recovery and resource recovery efficiency. For some extreme industrial streams, new PVDF membranes provide a reliable tolerance against high concentrations of acid or base substances without irreversible fouling[iv], and ceramic membrane can withstand more extreme conditions in a long lifespan.

Advanced oxidation processes

Many industrial sectors release wastewater containing recalcitrant or even toxic organic contaminants inhibiting biological activities and consequently resulting in low quality effluents after biological treatment. To tackle this challenge, advanced oxidation processes, such as the Fenton, UV/H_2O_2, catalytic ozonation, have been increasingly applied as pre-treatment to enhance the biodegradability or as post-treatment to further purify the secondary effluent, thanks to the generation of OH (E_o = 2.8 V) or other strong oxidative species (e.g. $1O_2$, SO_4-). Catalytic ozonation, as an example, has been widely applied in China as a tertiary step in centralised industrial wastewater treatment plants (WWTPs). A typical study revealed that ozonation catalysed with MnCe@Al_2O_3 achieved 50~60% removal of COD from bio-treated coking wastewater (95–195 mg L–1 COD) at full scale[v]. Nevertheless, the long-term catalyst stability is still a challenge, and the possible generation of toxic transformation products is also of great concern[vi].

Biological processes

Activated sludge is still a core unit in most industrial WWTPs where biodegradable organics and nutrients are effectively removed by microbes. Concerning process effluents with a high level of organics, high-rate anaerobic reactors (EGSB, IC, anMBR) are usually applied with >80 % conversion of biodegradable COD to biogas at high loading rates (15–30 kg COD m^{-3} d^{-1}). Recently aerobic granular sludge (AGS) has been gaining ground for the simultaneous removal of P, N, and organic contaminants. For the treatment of ammonia-rich effluent which occurs frequently in industrial sectors like livestock and poultry industry and coal-to-chemical processes, several ANAMMOX processes (CANON, OLAND, SHARON, DEMON, SNAD) have shown great potential at pilot or full scale as a low-carbon nitrogen removal technology[vii].

Resource recovery

Industrial effluents contain a high content of organics, metals, and nutrients and thus are increasingly viewed as a valuable resource rather than a waste stream[viii]. It is well known that anaerobic digestion can generate biogas for heat and power recovery with effluents containing a high concentration of easily biodegradable organics (e.g. from breweries, dairies). Nutrients such as nitrogen and phosphorus can be extracted from food-processing wastewater to produce fertilisers (e.g. struvite). Metals (e.g. copper, zinc) from electroplating or mining effluents are recovered through adsorption, ion-exchange, or precipitation. Alginate, cellulose, and bioplastics like polyhydroxyalkanoates can also be harvested from organic-rich industrial effluents[ix]. It is worth mentioning that resources recovery from wastewater can significantly minimise entropy production and thus reduce the climate risks associated with effluent treatment[x].

Brine management

In water-scare regions, water-intensive industry is likely to implement zero-liquid discharge to balance the local water supply and economic development. Nearly 100% of water can be recovered with the crystallisation of salts present in the original wastewater. A major hurdle is the high energy consumption, especially from thermal processes like evaporators (e.g. mechanical vapour recompression, MVR; multi effect distillation, MED) and crystallisers which account for >40% of energy of treating brine[xi]. Treating complex industrial effluents with high salinity and diverse organic and inorganic contaminants poses another difficulty. Membrane-based pre-concentration steps, such as reverse osmosis, are often limited by fouling and scaling, which reduce efficiency and require frequent chemical cleaning. Furthermore, the reuse potential or market value of recovered salts remains a critical issue since the salts may be of low purity, complicating their reuse or disposal.

Emerging industrial sectors and demands

Semiconductor industry

The semiconductor production is largely dependent on ultrapure water (total organic carbon, TOC <3 µg/L, conductivity <0.055 µS $cm^{-1)}$ in many critical steps such as wafer rinsing, preparing chemical solutions, or immersing the photolithography. The average ultra-pure water consumption per unit area of wafer is about 7~8 L/cm^2.To prepare ultra-pure water, multi-step purification (reverse osmosis, oxidation, ion exchange, etc.) is often used, which is energy- and chemical-intensive. Effluents from the semiconductor industry contain toxic heavy metals (e.g. arsenic, copper), fluorides, solvents (e.g. isopropyl alcohol, dimethyl sulfoxide), and perfluorinated compounds[xii]. These contaminants are difficult to remove with conventional biological treatment, thus requiring advanced physical-chemical methods.

Data-centre cooling water

Data centres consume substantial volumes of water for cooling. The cooling water use is estimated to be 1.8 litres per kWh of the total data power usage. It is reported that Google's data centres in the USA used over 30 billion litres of water in 2019 and another 3 billion litres of water in other regions[xiii]. Water-treatment challenges here include continuous dosing of corrosion inhibitors, anti-scalants, and biocides, which raise environmental concerns. Using alternative water sources (e.g. reclaimed treated wastewater) introduces impurities that complicate treatment and increase the risk of scaling and biofouling. Advanced approaches such as closed-loop cooling and real-time optimisation of water and energy use can be adopted to mitigate these challenges.

Bio-manufacturing

Bio-manufacturing or biologicalisation usually refers to the application and integration of biological and bio-inspired principles, materials, functions, structures, and resources from living nature for intelligent and sustainable production[xiv]. Bio-manufacturing relies heavily on renewable biological resources, such as biomass, nutrients, and water as primary feedstocks. The shift toward a circular bio-economy also increases the need to recover these resources from waste streams, especially water and nutrients. For instance, to produce 1000 kg cultured meat from muscle cell growth, 367–521 m^3 water is required, besides other resources[xv]. The cultivation broth contains a lot of dissolved proteins and nutrients, leading to a new challenge of reuse of water and other substances.

New-energy sector

Renewable and unconventional energy sources have been promptly developed from various sources such as solar, wind, biomass, geothermal, and nuclear fusion. The global capacity of photovoltaics systems has increased ten-fold during the past decade. Photovoltaic cell manufacturing consumes large volumes of ultra-pure water for silicon purification and wafer cleaning. Wastewater from this process contains acids, alkalis, solvents, and heavy metals, e.g. from etching and texturing. A significant challenge is fluorine in wastewater ranging from 200 to 2000 mg/L[xvi]. On the other hand, the massive production of lithium ion batteries as response to the roaring demand for electricity storage also needs a lot of water, especially in electrode coating, slurry preparation, and cell assembly. The water footprint of a traction battery pack is significant, with wastewater streams containing organic solvents like N-methylpyrrolidone, binders, and metal ions (Li, Ni, Co) that challenge conventional biological treatment. Efficient removal of these recalcitrant compounds often demands advanced oxidation, adsorption, and membrane processes. Special attention should be paid on the effluent generated during the recycling of spent battery and photovoltaic cells[xvii].

Regulatory gaps

Industrial production can lead to various emerging organic contaminants such as polyfluoroalkyl substances (PFAS) and endocrine disrupting chemicals which can be transported across nations via trading and supply chains. Thus, an international cooperation regulation is in need to control the application of priority chemicals. Moreover, discharging brine into receiving water bodies like oceans or brine lakes can cut down the energy consumption of evaporation but discharging standards are not in position in many regions. In addition, the quality of salt recovered from waste streams has not been standardised, making it difficult to reuse the salt in industrial production or domestic applications. Disposing salt as hazardous waste obviously conflicts with the principle of circular economy.

Case study: photovoltaic cell manufacturing effluent

Photovoltaic cell manufacturing effluent is mainly released from silicon texturing with KOH and isopropanol, pickling with HF and HNO_4, etching with HF, and cleaning steps. Consequently, a high content of alkaline, acid, and fluorine can be expected. Table 4.1 presents the typic composition and flow rates of separately collected effluents in a manufacturer in China[xviii]. Extremely high levels of fluorine and total nitrogen (TN) are the main challenges for efficient effluent treatment. The treatment process in this case includes multi-step coagulation with $CaCl_2$, polyaluminium chloride (PAC), polyacrylamide (PAM) to remove fluorine, acidification to enhance biodegradability, and concocted treatment with household effluent to balance the nutrition. Finally, the treated effluent is discharged into the local sewage system. Typical operational problems of this treatment process are the shocking of biological process by H_2O_2 regularly applied as a cleaning agent and the sludge bulking likely due to the shortage of P and other elements.

Table 4.1 Characteristics and flow rates of separately collected effluents in a photovoltaic cell manufacturer in China.

Type	Flow	pH	COD	F	TN
	(m^3 d-1)		(mg·L-1)	(mg·L-1)	(mg L-1)
Alkaline effluent	700±100	12~14	60±30	45±25	350±50
Acidic effluent	900±100	<2	50±20	6000±2000	1300±200
Other process effluent	3,000±300	3~4	40±20	70±30	200±50
Household effluent	400±50	6~9	350±50	—	30±5

Conclusions and outlook

Industrial water management is transitioning from a linear "supply-treat-use-treat-discharge" paradigm to a resilience-oriented, circular-economy framework. Membrane separation, catalytic oxidation, and efficient biotreatment have already pushed the removal of conventional contaminants, the separation of salts, and resources recovery to technical maturity; nevertheless, the rapidly increasing water footprint of emerging industries such as semiconductor fabs, gigafactories for batteries, and bio-manufacturing brings up new technical challenges and regulatory demands. Future R&D activities should therefore integrate multi-dimensions: (1) precise separation and recovery of valuables from complex matrix; (2) low-entropy brine crystallisation and valorisation; (3) systematic calculation and simulation to merge the material inventory databases of production processes and the control of water treatment processes towards reduction of energy and material consumption; and (iv) international instruments to track and manage emerging contaminants through global supply chains.

References

[i] UN World Water Development Report 2025, https://www.unwater.org/publications/un-world-water-development-report-2025

[ii] Q. Wang, N. Huang, Z. Chen, X. Chen, H. Cai, Y. Wu, Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation. *Water Cycle*, 2023, 4, 47-54. https://doi.org/10.1016/j.watcyc.2023.01.004

[iii] J. Li, W. Cheng, H.. Wang, Y. Luo, Q. Liu, X. Wang, L. Wang, T. Zhang, Reverse osmosis and nanofiltration processes in industrial wastewater treatment: The recent progress, challenge, and future opportunity. *Separation and Purification Technology*, 2025, 362, 131687. https://doi.org/10.1016/j.seppur.2025.131687.

[iv] D. Zou, Y. M. Lee, Design strategy of poly(vinylidene fluoride) membranes for water treatment. *Progress in Polymer Science*, 2022, 128, 101535. https://doi.org/10.1016/j.progpolymsci.2022.101535.

[v] C. He, J. Wang, C. Wang, C. Zhang, P. Hou, Xi. Xu, Catalytic ozonation of bio-treated coking wastewater in continuous pilot- and full-scale system: Efficiency, catalyst deactivation and in-situ regeneration. *Water Research*, 2020, 183, 116090, https://doi.org/10.1016/j.watres.2020.116090.

[vi] Y. Zhang, Z. Chen, X. Cao, Z. Xu, A. Xu, Y. He, Q. Zhang, S.-U Geissen, Y. Zhang, Enhanced detoxification of enrofloxacin during confined catalytic ozonation. *Chemical Engineering Journal*, 2025, 524, 169328, https://doi.org/10.1016/j.cej.2025.169328

[vii] M. Adams, E. Issaka, C. Chen, Anammox-based technologies: A review of recent advances, mechanism, and bottlenecks, *Journal of Environmental Sciences*, 2025, 148, 151-173, https://doi.org/10.1016/j.jes.2024.01.015.

[viii] S. Das, M. P. Shah, *Resource Recovery from Industrial Wastewater through Microbial Electrochemical Technologies*, 2024, IWA Publishing, https://doi.org/10.2166/9781789063813

[ix] G. Mannina, D. Presti, G. Montiel-Jarillo, J. Carrera, M. E. Suárez-Ojeda, Recovery of polyhydroxyalkanoates (PHAs) from wastewater: A review. *Bioresource Technology*, 2020, 297, 122478. https://doi.org/10.1016/j.biortech.2019.122478.

[x] X. Hao, J. Li, R. Liu, M. van Loosdrecht, Resource recovery from wastewater: what, why, and where? E*nvironmental Science & Technology*, 2024, 58, 32, 14065–14067, https://doi.org/10.1021/acs.est.4c05903.

[xi] T. Tong, L. Xu, T. Horseman, P. Westerhoff, P. Xu, Y. Yao, X. Zhang, R. Alghanayem, S. Lin. Brine management with zero and minimal liquid discharge. *Nature Reviews Clean Technology*, 1, 185–200 (2025). https://doi.org/10.1038/s44359-025-00036-2

[xii] S. Sandhu, A. Zumeit, Z. Tian, V. Vinciguerra, R. Dahiya, Semiconductor manufacturing wastewater challenges and the potential solutions via printed electronics. *iScience*, 2025, 28, 113576, https://doi.org/10.1016/j.isci.2025.113576

[xiii] R. Jha, R. Jha, M. Islam, Forecasting US data center CO_2 emissions using AI models: emissions reduction strategies and policy recommendations. *Frontiers in Sustainability*, 2025, https://doi.org/10.3389/frsus.2024.1507030

[xiv] E. Asin-Garcia, J. D. Fawcett, C. Batianis, V. A.P. M. dos Santos, A snapshot of biomanufacturing and the need for enabling research infrastructure. *Trends in Biotechnology*, 2025, 43, 1000-1014, https://doi.org/10.1016/j.tibtech.2024.10.014.

[xv] H. L. Tuomisto, M. J. T. de Mattos, Environmental impacts of cultured meat production. *Environmental Science & Technology*, 2011, 45, 6117–6123, https://doi.org/10.1021/es200130u

[xvi] X. Gao, Q. Wu, B. Zhou, Z. Yuan, N. Gai, R. Yuan, Z. Chen, S. Luo, H. Chen, Research status of typical wastewater treatment technology for photovoltaic cell production process. *Chemical Engineering Journal*, 2024, 499, 156523, https://doi.org/10.1016/j.cej.2024.156523.

[xvii] M. Ullah, H. Shalchian, T. Younas, F. Vegliò, N. M. Ippolito, Sustainable wastewater treatment in lithium-ion battery recycling: Processes, challenges, and innovations. *Process Safety and Environmental Protection*, 2025, 202, 107710, https://doi.org/10.1016/j.psep.2025.107710.

[xviii] L. Chen, W. Zhang, Y. Shen, B. Zhou, Practical operation of solar battery wastewater treatment plant. *Industrial Water Treatment*, 2022, 42(2): 168–172 https://link.cnki.net/doi/10.19965/j.cnki.iwt.2021-0493.

| 4.6 |

The circular economy as a paradigm for sustainable water management

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Introduction

The convergence of climate change, population growth, and urbanisation is exerting an unprecedented pressure on global water systems. At the same time, conventional wastewater treatment remains energy-intensive, carbon-emitting, and fundamentally linear – designed to remove pollutants rather than recover value.

A paradigm shift is therefore required: from wastewater treatment to circular water management. This new approach is necessary to address water scarcity, achieve climate goals, and enhance resource security.

Urbanisation, while increasing demand for large-scale water services, also creates a critical opportunity to concentrate and integrate resource recovery processes with the systems that utilise them. Circular water systems are thus not only a response to scarcity, but a foundation for resilient, low-carbon, and resource-efficient urban development.

A framework for circular water management

Moving towards a circular economy for water requires proactively closing the loops on several key resource streams present in wastewater. Sustainable water management must pivot to recover and reuse.

- **Water:** transitioning from waste discharge to a reliable source of potable and non-potable water
- **Nutrients (N, P):** for food system resilience
- **High-value products:** e.g. cellulose from toilet paper, volatile fatty acids (VFAs), and metals
- **Energy:** optimisation of system efficiency to reduce greenhouse gas (GHG) emissions

The success of circular systems should be measured first by their ability to deliver safe, scalable water reuse, with other recovery pathways enhancing overall system performance.

Water reuse: from compliance to strategic supply

Water reuse is the foundation of circular water management systems and the primary mechanism for transforming wastewater into a strategic resource. This report explores the technologies and strategies enabling this shift, beginning with the most fundamental resource: water itself.

Water reuse has evolved significantly over the past three decades. Initially driven by discharge compliance – particularly nutrient removal – reuse is now increasingly recognised as a strategic component of water supply portfolios.

Growing water scarcity, climate variability, and rising demand have accelerated this shift. Reuse now spans a continuum:

- Non-potable reuse (agriculture, landscaping, industry)
- Indirect potable reuse (IPR)
- Direct potable reuse (DPR).

This evolution reflects a fundamental change: from substituting potable water to augmenting total water availability.

Circular water systems rely on a portfolio of reuse solutions adapted to context (fit for purpose):

- Advanced treatment systems (e.g. membrane-based processes) enable high-quality reuse, including potable applications and high-quality water for the industry (e.g., semiconductor)
- Managed aquifer recharge (MAR) provides storage, buffering and risk mitigation
- Nature-based systems offer cost-effective reuse for agriculture and ecosystem restoration.

The selection of reuse pathways depends on:

- Water scarcity levels
- Economic capacity
- Regulatory frameworks
- Intended end-use.

In all cases, reuse must be positioned as a core infrastructure strategy, not a niche or supplementary option.

The sustainability challenge of conventional treatment

Conventional activated sludge systems present three fundamental limitations:

1. High energy demand, particularly for aeration
2. Destruction of embedded resource value, especially organic carbon and phosphorus
3. GHG emissions, notably nitrous oxide (N_2O), which prevent net-zero outcomes

Although wastewater contains significant embedded energy, conventional processes consume energy to oxidise organic matter rather than recover it. This structural inefficiency highlights the need for treatment systems designed around resource recovery and reuse, rather than pollutant removal alone.

Resource recovery to enable circular water systems

1. Nutrients: – closing the food-water loop

Wastewater represents a significant and underutilised source of nutrients:

- Phosphorus recovery could meet up to 15–20% of global demand
- Nitrogen recovery can offset energy-intensive fertiliser production (Haber-Bosch process).

Current systems remove nutrients at high energy cost, only to replace them industrially. Circular approaches reverse this logic, linking wastewater management directly to food system sustainability.

KEY ACTIONABLE PATHWAYS INCLUDE:

- Struvite precipitation for phosphorus recovery
- Ammonia recovery via membrane processes, ion exchange, or stripping.

Anaerobic treatment systems enhance these opportunities by releasing nutrients into soluble forms, facilitating recovery. Positioning nutrient recovery within circular water systems strengthens both food security and climate mitigation.

2. Value-added products

Wastewater contains several material streams that can be recovered to support circular industrial systems, although these remain secondary to water and nutrient recovery. Cellulose (e.g. from toilet paper) can be recovered early to reduce treatment loads and supply industrial uses (Wiśniowska and Kowalczyk, 2022). VFAs can serve as substrates for various biochemical processes, including biopolymer and bioenergy production (Mineo et al., 2024; Puyol, 2017). Metals can be recovered from increasingly concentrated brines.

3. Nature-based and low-tech options

Nature-based and low-tech solutions are increasingly recognised as context-specific circular systems, particularly for small and medium-scale applications.

These include:

- Constructed and floating wetlands
- Lagoon upgrades with algae-based systems
- Soil-aquifer treatment and MAR.

Recent work has shown that constructed (including floating) wetlands are becoming more viable and cost-effective as nature-based treatment options. In managed aquifer recharge, recent research is tackling risks, optimising recharge methods, and integrating data-driven tools. Key trends include the increased use of machine learning/predictive modelling for planning and controlling recharge operations and a better understanding of hydrogeological heterogeneity.

While the strengths of these low-tech solutions lie in lower cost and energy requirements, climate resilience, and co-benefits (biodiversity, carbon sequestration), particularly for small communities and resource-constrained settings, there are limited opportunities to recover other resources, including high-quality reclaimed water. There are options for utilising low-grade irrigation water for agricultural purposes and for nutrient recovery through the periodic harvesting of plant material.

Energy recovery within circular water systems

Energy recovery aims to improve efficiency and reduce emissions in circular water systems.

Three pathways stand out:
- Anaerobic digestion
- Anaerobic membrane bioreactor
- Heat recovery

Anaerobic digestion

The well-established method for energy recovery from domestic wastewater is anaerobic digestion of primary settled sludge, and in some cases, the addition of small quantities of waste-activated sludge. This technology poses significant sustainability threats, including the potential fugitive leakage of biogas into the atmosphere from digestors and dissolved gases in the supernatant.

Anaerobic membrane bioreactor

The anaerobic membrane bioreactor (AnMBR) is emerging as a key transition pathway toward energy-efficient, resource-recovery treatment systems compared to aerobic MBRs. It has significant potential as a sustainable treatment process, especially when compact solutions are desired (e.g. in densely populated urbanised environments). In addition to its ability to remove a broad range of trace organic contaminants, an AnMBR can convert organics to biogas and release nutrients to soluble forms (e.g. ammonia and phosphorus) for subsequent recovery (Song et al., 2018).

This synergy between energy recovery and nutrient liberation makes AnMBRs a cornerstone technology for the circular economy, though their full viability depends on integrating subsequent nutrient recovery processes to handle the nutrient-rich effluent.

The potential to retrofit existing plant infrastructure, such as sedimentation tanks, with AnMBR technology is also a benefit that warrants further exploration.

Heat recovery

Heat recovery, which captures thermal energy from wastewater using heat pumps, is among the most immediately deployable and scalable energy optimisation options, particularly in urban systems.

EMERGING ENERGY RECOVERY OPTIONS

Several innovative technologies, under development, show long-term potential and may contribute to future systems.

- **Microbial fuel cells:** Like chemical or hydrogen fuel cells, the microbial fuel cell (MFC) utilises the microbial metabolism of organic pollutants to directly convert the chemical energy in wastewater into electrical energy while reducing contaminants. MFCs can remove nearly 70% of the chemical oxygen demand (COD), but they do not efficiently convert the removed organics into electrical energy (Bird et al., 2022). They suffer from scalability issues and difficulty allowing microorganisms to thrive in environments that are typically not optimal for life (acidic pH, high salinity).
- **Photocatalytic conversion:** The potential to oxidise pollutants and convert the resulting CO_2 to high-energy compounds, such as CO or CH_4, in a single reactor using multiple photocatalysts has been demonstrated (Zou et al., 2016; Zheng et al., 2024).
- **Thermal difference:** The embedded potential energy from the temperature difference between sewage and the discharge environment can be converted to an electrical current using a thermoelectric generator.
- **Forward osmotic pressure:** The salinity gradient that occurs when effluent from a wastewater treatment plant discharges to the environment has significant energy potential that can be recovered.

Case study: quantifying the resource recovery potential

The potential resources in a typical wastewater treatment plant have been estimated to illustrate the opportunities for greater resource recovery (Muston, 2025). The Wollongong Water Resource Recovery Facility is a coastal treatment plant serving a population of 200,000 and receiving an inflow of 49,800 m^3/day (Sydney Water, 2024). The plant is already recognised as a positive example of water reuse and energy recovery. It recycles almost half of the normal inflow.

Table 4.2 quantifies this potential, highlighting the gap between current performance based on publicly available data from Sydney Water (2024) and what is theoretically achievable with a shift towards a resource recovery paradigm.

Table 4.2 Wollongong Water Resource Recovery Facility daily resource potential

Parameter	Assumption	Theoretical yield
Inflow		49,800 m^3/day
COD	430 mg/L	21.4 × 10^3 kg/day
Energy from COD	1.76 kWh/kg COD	38 MWh
Energy from temperature differential	4,200 kJ or 1.7 kWh /kg/°C	36 MWh/°C/day
Energy from forward osmot-ic pressure	0.75 kWh/m^3 of freshwater discharged to sea	16 MWh/day
Total theoretical potential energy		90 MWh/day
Current average energy recovery		10 MWh/day
Other theoretical potential resources		
Nitrogen	TKN 30 mg/L	1,500 kg/day
Phosphorus (dissolved)	8 mg/L inflow	400 kg/day
Phosphorus, including cell content	40 mg/L	2,000 kg/day
Cellulose	50% of TSS – 125 mg/L	6,200 kg/day
VFAs	55 mg/L average	2,700 kg/day

This case study demonstrates the scale of the opportunity and the need for system redesign to prioritise reuse and integrated recovery. Several trial projects are being developed globally to demonstrate the potential for resource recovery. An example is blue water factories in China (Hao et al., 2023).

A roadmap for implementation: research and policy

Research priorities

INTEGRATED TREATMENT SYSTEMS

AnMBRs offer substantial energy-efficiency advantages compared to anaerobic MBRs. Nevertheless, improving system stability and performance remains challenging. Future research should therefore prioritise biological strategies to broaden the feasible operational temperature range.

Moreover, nitrogen and phosphorus present in AnMBR effluent represent valuable resources that require efficient recovery approaches. Advanced processes should be further developed and integrated with AnMBRs to enhance nutrient recovery while ensuring effluent quality that meets discharge standards or reuse guidelines (Park et al., 2024).

Further research is also needed on the improved design and configuration of AnMBR systems, with particular emphasis on incorporating integrated resource recovery modules. Additionally, biogas upgrading should be a key area of focus to also reinforce their role in supporting circular economy principles.

ALGAL AND BIO-BASED SYSTEMS

Algal-based treatment for nutrient removal and recovery has been widely investigated in recent years (Acién Fernández et al., 2018; Nguyen et al., 2022; Usman et al., 2023), particularly using microalgae. Microalgae not only facilitate nutrient recovery but also serve as a promising feedstock for biofuel production (mostly biodiesel).

Currently, conventional municipal wastewater treatment primarily focuses on removing nitrogen and phosphorus through biological denitrification and chemical precipitation, rather than recovering them. Even advanced processes, such

as ANAMMOX, remain removal-oriented, albeit with reduced energy demand due to shortcut denitrification compared to conventional nitrification-denitrification pathways.

Future research should prioritise the isolation and development of highly active algal species with high yields and high triglyceride content, as well as enhanced nutrient recovery capacity, thereby advancing sustainable, resource-efficient wastewater treatment.

Policy and economic enablers

The proper valuation of water is essential to ensure its sustainable use. Appropriate pricing can incentivise responsible consumption and reduce wastage. At the same time, access to water for all must remain a fundamental principle.

Beyond water pricing, policy must actively drive the transition to a circular economy. This includes:

- Creating "Resource Recovery Credits" or similar mechanisms to value recovered nutrients, energy, and carbon, creating a market for these products.
- Updating regulations to fast-track the safe use of recovered products, such as struvite fertilisers and reclaimed cellulose.
- Mandating life-cycle assessment and GHG accounting for wastewater treatment, making the environmental cost of the current linear system visible.
- Providing grants and low-interest loans for utilities to retrofit existing infrastructure with modular resource recovery technologies.

Critically, policy must prioritise reuse markets first, with resource recovery as a reinforcing mechanism.

Conclusions and the path forward

This report highlights key messages and underscores the importance of integrated approaches grounded in circular-economy principles to secure water resources and enhance climate resilience.

Water reuse must be the central objective, forming the backbone of circular systems. Water reuse must evolve from a compliance-driven activity to a core strategy for augmenting reliable, high-quality supply, including direct and indirect potable reuse. A portfolio of reuse solutions, ranging from advanced membrane systems to nature-based approaches, is essential, with the choice determined by scale, context, and specific needs.

Nutrient and material recovery enhance sustainability and economic viability. N and P should be treated as resources, not pollutants. Anaerobic processes (e.g. AnMBRs) release these in soluble form, enabling recovery as fertilisers (e.g. struvite) through membrane processes, ion exchange, or electrodialysis. Algal-based processes also offer dual pathways for nutrient recovery and biofuel production.

Energy recovery plays a supporting, optimisation role. Wastewater contains more chemical and thermal energy than is currently recovered. Transitioning from aerobic activated sludge to anaerobic membrane bioreactors (AnMBRs) can cut energy use and boost energy recovery through biogas and other streams (heat differentials, salinity gradients, microbial/photocatalytic routes). Upgrading biogas and integrating with hydrogen systems can further enhance net energy gains.

System integration design is essential for unlocking full value. Retrofitting existing plants with modular recovery technologies is crucial for achieving net-zero goals. Co-location with industries or energy systems (e.g. hydrogen electrolysis, district heating) can maximise synergies.

Policy and equity are essential for scaling implementation. Effective water valuation and pricing reforms to incentivise reuse, targeted subsidies, and supportive policies are crucial for promoting proper water use and resource recovery while ensuring equitable access to water.

Moving forward, the transition to circular water systems will be essential for achieving water security, climate goals, and sustainable development.

References

Acién Fernández, F.G., Gómez-Serrano, C., Fernández-Sevilla, J.M., 2018. Recovery of nutrients from wastewaters using microalgae. *Frontiers in Sustainable Food Systems*, 2, 59. https://doi.org/10.3389/fsufs.2018.00059.

Bird, H., Heidrich, E., Leicester, D., Theodosiou, P., 2022. Pilot-scale microbial fuel cells (MFCs): A meta-analysis study to inform full-scale design principles for optimum wastewater treatment. *Journal of Cleaner Production,* 346, 131227.

Center for Water and Environmental Biotechnology, University of Queensland, 2025. Webpage https://acweb.uq.edu.au/project/transforming-wastewater-treatment-regional-australia-robust-technology-multiple-benefits?utm_source=chatgpt.com (accessed 16/9/2025).

Hao, X., Ji Li J., Wu, Y., Liu, R., Cai, R., 2023. Blue water factories in China: The future of wastewater treatment. *The Source*. IWA Publishing, July 2023.

Mineo, A., Cosenza, A., Ng, H., Mannia, G., 2024. Volatile fatty acids from sewage sludge by anaerobic membrane bioreactors: Lessons learned from two-year experiments with fouling analysis by the resistance in series model. *Results in Engineering*, 21, 101839.

Muston, M., 2025. Beyond water– changing the paradigm of reuse. *Water Reuse*, 15(3), 546. doi: 10.2166/wrd.2025.052

Nguyen, L.N., Aditya, L., Vu, H.P., Johir, A.H., Bennar, L., Ralph, P., Hoang, N.B., Zdarta, J., Nghiem, L.D., 2022. Nutrient removal by algae-based wastewater treatment. *Current Pollution Reports*, 8(4), 369–383. https://doi.org/10.1007/s40726-022-00230-x.

Park, H.-J., Park, H., Kim, J., Lee, K., Naddeo, V., Choo, K.-H. 2024. Enhancing sustainability: Upcycled membrane distillation for water and nutrient recovery from anaerobic membrane bioreactor effluent. *Chemical Engineering Journal*, 498, 155267. https://doi.org/https://doi.org/10.1016/j.cej.2024.155267.

Puyol, D., Batstone, D.J., Hülsen, T., Astals, S., Peces, M., Krömer, J,O., 2017. Resource recovery from wastewater by biological technologies: Opportunities, challenges, and prospects. *Frontiers in Microbiology*, 16, 2106.

Seebeck, T. J., 1825. Magnetic polarization of metals and minerals by temperature differences. *Treatises of the Royal Academy of Sciences in Berlin*, 265–373 [in German)https://books.google.com.au/books?id=E27NAAAAMAAJ&pg=PA265&redir_esc=y#v=onepage&q&f=false (Accessed 21/11/2024).

Song, X., Luo, W., Hai, F., Price, W., Guo, W., Ngo, H., Nghiem, L., 2018. Resource recovery from wastewater by anaerobic membrane bioreactors: Opportunities and challenges. *Bioresource Technology*, 270, 669–677.

Sydney Water, 2024. Wollongong Water Resource Recovery Facility. https://www.sydneywater.com.au/education/wastewater-recycling/water-recycling/wollongong-water-recycling-plant.html (Accessed 20/11/2024)

Usman, M., Amin, M., Kamal, I., Shahid, A., Xu, J., Alam, M.A., Mehmood, M.A., Ashraf, G.A., Boopathy, R. 2023. Algae-mediated resource recovery from urban wastewater. *Current Pollution Reports*, 9(2), 243–258. https://doi.org/10.1007/s40726-023-00254-x.

Wiśniowska, E., Kowalczyk, M., 2022. Recovery of cellulose, extracellular polymeric substances and microplastics from sewage sludge: A review. *Energies*, 15(20), 7744, https://www.mdpi.com/1996-1073/15/20/7744.

Wu, H., Kim, T., Ferdous, S., Scheve, T., Lin Y., Valentino, L., Holtzapple, M., Hawkins, T., Benavides P., Urgun-Demirtas M., 2024. Sustainable aviation fuel from high-strength wastewater via membrane-assisted volatile fatty acid production: Experimental evaluation, techno-economic, and life-cycle analyses. *ACS Sustainable Chemical Engineering*, 12, 6990−7000.

Zheng, L., Tian, L., Zhang,L., Yu, J,. Chen,Y., Fu, Q., Liu, X, Wu, D., Zou, J., 2024. Defect-induced synergetic effect of Bi-based compounds for one-pot conversion of organic pollutants into CO via coupling photodegradation of carbamazepine with photoreduction of CO_2. *ACS Catalysis*, 14, 2134−2143.

Zou, J., Wu, D., Luo, J., Xing, Q., Luo, X., Dong, W., Luo, S., Du, H., Suib, S., 2016. A strategy for one-pot conversion of organic pollutants into useful hydrocarbons through coupling photodegradation of MB with photoreduction of CO_2. ACS *Catalysis*, 6, 6861



| 5 |

Water governance, finance, and equity

| 5.1 |

Benchmarking, performance assessment and regulation of urban water systems

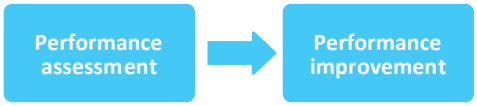
Authors: *Enrique Cabrera Jr., Peter Dane, Elvira Estruch-Juan, Shuang Li, Alan Wyatt on behalf of the Specialist Group on Benchmarking and Performance Assessment*

Introduction

Benchmarking was originally developed by the Rank Xerox company in the 1970s as a management tool to respond to increasing competition and to improve products and services (Camp, 1989). It was not until the late 1990s that benchmarking was introduced into the water sector. Since then, the number of benchmarking initiatives has grown substantially, not only among water and wastewater utilities and their professional associations, but also among other stakeholders such as governmental bodies and regulators, thus evolving into a multi-stakeholder instrument. In many cases, these initiatives remain limited to performance assessment, while more mature forms of benchmarking (performance improvement) are still applied in a relatively small number of cases.

In the early 2000s, the International Water Association (IWA) published manuals on performance indicators for drinking water and wastewater services, which remain widely used as a global reference for the selection of indicators for self-assessment and benchmarking (Alegre et al., 2000; Matos et al, 2003).

Since 2009, the IWA Specialist Group on Benchmarking and Performance Assessment (SG BPA), and its predecessor, the IWA/AWWA Task Group on Benchmarking, have supported the global water community in the application of benchmarking as a management instrument for improving water services. One of the first contributions of the group was the development of a common benchmarking framework, defining benchmarking as "a tool for performance improvement through the systematic search for and adaptation of leading practices, improving water services by learning from each other" (Cabrera et al., 2011). For benchmarking to be effective, two consecutive steps are required: performance assessment and subsequent performance improvement.



Beyond the development of frameworks and indicators, the SG BPA places strong emphasis on dissemination and knowledge exchange, notably through the organisation of its biennial PI Conferences: "Conference on Benchmarking, performance Assessment and Regulation" and thematic webinars.

Benchmarking

Over recent years, benchmarking in the urban water sector has continued to expand globally, consolidating its role as a key instrument for performance assessment and, to a lesser extent, performance improvement. Most benchmarking activities worldwide are organised as recurring reporting cycles, led by water and wastewater utilities, their professional associations, regulators and, increasingly, multi-stakeholder platforms. Despite this expansion, a significant share of initiatives still focuses primarily on data collection and performance assessment, while more mature benchmarking approaches – linking assessment to performance improvement actions – remain less widespread.

In Europe, benchmarking remains well established through national programmes, typically facilitated by national water utility associations. These programmes provide stable frameworks for performance comparison and peer learning, although their levels of maturity and methodological depth vary considerably. Even in this relatively advanced context, further professionalisation and deeper integration of benchmarking results into management and regulatory processes are still needed.



Figure 5.1: EBC's annual benchmarking workshop in November 2025 in Nieuwegein (NL)

At the international level, additional benchmarking initiatives complement national programmes by enabling cross-country comparison and knowledge exchange. In this context, collaborative platforms involving utilities from different European countries, and occasionally beyond Europe, provide opportunities for sharing practices and harmonising performance assessment approaches, thereby reinforcing learning processes beyond national boundaries.

In China, recent benchmarking developments reflect a clear shift towards integrated performance assessment frameworks. Benchmarking and performance evaluation are increasingly aligned with broader policy objectives, notably the integration of carbon reduction, pollution control, and energy efficiency into unified assessment schemes. This evolution illustrates a broader trend towards multi-dimensional benchmarking approaches that support the achievement of sustainability objectives under SDG 6 and related climate goals (GB/T 46725-2025).

Beyond Europe and China, performance assessment initiatives across other regions show several common patterns. In North America, these activities are largely based on standardised indicator sets and regular sector-wide surveys, enabling utilities to assess their performance by size, service type and context, and to monitor trends over time (AWWA Utility Benchmarking Program, 2025). In Latin America and the Caribbean, performance assessment is closely linked to regulatory and regional coordination frameworks, supporting transparency, comparability and evidence-based decision-making, while providing a foundation for more structured benchmarking exercises. In Australia, benchmarking is institutionalised through comprehensive national performance reporting, enabling consistent long-term performance tracking (Australian Bureau of Meteorology, 2024). In Africa and other emerging contexts, benchmarking and performance assessment have gained increased attention (ESAWAS, 2024), although limitations in data availability and consistency continue to constrain their maturity.

At the global level, benchmarking is increasingly supported by international datasets and harmonised indicator frameworks that facilitate cross-country comparison and trend analysis, while also highlighting persistent gaps in data coverage and the limited translation of assessment results into performance improvement.

Regulation

Over recent years, regulation of urban water and wastewater services has continued to evolve from a predominantly compliance- and tariff-focused function towards a broader role combining economic regulation, service quality oversight, sustainability objectives, resilience, and, increasingly, data-enabled supervision.

A key development has been the strengthening of regional cooperation among regulators. Networks such as WAREG in Europe and ADERASA and RegWAS LAC in Latin America illustrate the growing emphasis on coordination, shared learning, and harmonisation of regulatory approaches. These platforms support the exchange of regulatory practices, performance assessment methodologies, and evidences across jurisdictions.

Regulatory agendas have also expanded in scope. Increasing attention is being paid to long-term investment planning, environmental performance, and emerging challenges such as new pollutants and climate adaptation. Performance-based regulatory approaches are increasingly used to link tariffs, investment allowances, and service outcomes.

Digitalisation is progressively reshaping regulatory practice. Regulators are exploring ways to complement periodic reporting cycles with more continuous and data-informed oversight models, including access to operational and infrastructure management data from utilities. This evolution reinforces the importance of consistent performance indicators, robust data governance frameworks and closer alignment between regulatory requirements and benchmarking systems.

Future trends and challenges

Digitalisation and hybrid performance assessment

Benchmarking and performance assessment are increasingly shaped by rapid digitalisation. A central trend is the transition towards hybrid assessment models that combine well-established performance indicators with the growing availability of operational data, big data analytics, and digital tools. Dashboards, near-real-time monitoring and dynamic data queries are progressively supporting management and oversight, while traditional indicators continue to provide a stable and comparable reference framework.

Digitalisation in regulation and oversight

Digitalisation is also influencing regulatory practice. Regulators are gradually moving beyond periodic reporting towards more continuous and data-informed oversight, supported by access to utility operational and asset management data. While this creates opportunities for more timely supervision and early risk identification, it also requires clear data governance arrangements and shared understanding of data limitations and appropriate use.

Data quality, validation, and uncertainty

As data volumes and analytical capabilities expand, data quality and uncertainty management become central challenges. The effectiveness of benchmarking and regulation increasingly depends on systematic data validation, quality assurance, and explicit treatment of uncertainty at both utility and national levels. Without these safeguards, performance comparisons risk losing credibility and may fail to support sound decision-making.

Evolution of performance indicators

There is a growing demand for new performance indicators addressing emerging priorities such as asset management, sustainability, climate resilience and security of supply. While many core indicators are already mature and widely applied, new indicators must adhere to the same principles of clarity, consistency, comparability and methodological rigour that underpin existing key performance indicators (KPI) frameworks.

Water loss as a persistent and cross-cutting challenge

Water loss management illustrates the challenges of translating performance assessment into sustained performance improvement. While many high-income countries have achieved relatively low levels of water loss, significant losses persist in many low- and middle-income contexts, driven by limited technical capacity, financial constraints, and weak information bases. Fragmented institutional responsibilities, inconsistent application of best-practice indicators and insufficient attention to data quality further constrain effective management.

Addressing water loss requires integrated approaches linking benchmarking, regulation and operational improvement. Coordinated action among utilities, regulators, policymakers, and professional organisations – supported by robust data practices and digital tools – remains essential to move from monitoring towards durable performance gains.

Towards global connectivity and shared learning

Future progress will increasingly depend on improved connectivity and interoperability between benchmarking programmes and performance databases. The development of global or federated data platforms, enabling consistent indicator definitions and controlled data sharing, would strengthen cross-country learning and evidence-based policy development.

References

Alegre, H., Baptista, J. M., Cabrera, E., Cubillo, F., Duarte, P., Hirner, W., Merkel, W., & Parena, R. (2000). Performance Indicators for Water Supply Services. IWA Publishing.

Australian Bureau of Meteorology (2024). National Peformance Report: Water and wasterwater service providers (NPR)

AWWA (2025). Utility Benchmarking Program: Performance Management for Water and Wastewater.

Cabrera, E., Dane, P., Haskins, S., & Theuretzbacher-Fritz, H. (2011). *Benchmarking Water Services*. IWA Publishing.

Camp, R. C. (1989). Benchmarking: The search for industry best practices that lead to superior performance. American Society for Quality.

ESAWAS (2024). Regional benchmarking of water supply and sanitation utilities. 2022/2023 Report.

GB/T 46725-2025 – Synergistic Carbon Reduction Performance Evaluation for Urban Wastewater Treatment.

Matos, R., Cardoso, A., Ashley, R. M., Duarte, P., Molinari, A., & Schulz, A. (2003). *Performance Indicators for Wastewater Services*. IWA Publishing.

| 5.2 |

Economic and governance instruments for advancing circular water solutions: insights from WCEI and WICER

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Introduction

Circular water economy solutions have gained increasing relevance within the water sector as challenges related to water scarcity, declining water quality, rising energy prices, and escalating chemical costs have become more acute. Nevertheless, despite this favourable macro-level context, the implementation of circular water projects remains limited in most countries.

Strategies to Advance Circular Water Solutions

To navigate the challenges of advancing circular water solutions, stakeholders might consider the following strategies:

1	**Develop clear regulatory frameworks** that provide guidelines on reuse standards, quality assurance, and liability allocation to enhance investor confidence.
2	**Create partnerships between utilities and firms** to facilitate shared goals and responsibilities, ensuring that contractual agreements address the complexities of circular economy investments.
3	**Implement educational initiatives** aimed at improving financial literacy among utility managers, enabling them to better structure and present bankable propositions for circular projects.
4	**Foster community engagement** through transparent communication about the benefits and risks associated with circular water initiatives, promoting procedural fairness and inclusivity in decision-making processes.
5	**Explore the use of performance-based incentives or subsidies** that align the financial interests of investors and community stakeholders while encouraging sustainable practices in water management.

By adopting these strategies, decision-makers can better harness economic and governance instruments to support the transition to a circular water economy.

Within the European Union, only France, Greece, Portugal, and Spain have fully adopted the 2020 EU Water Reuse Regulation (European Parliament, 2020). Belgium, Hungary, and Italy have implemented the regulation only partially, while Malta has adopted it in practice without formal transposition, and Cyprus has implemented it through distributed regulatory arrangements (McLennan et al., 2024). Consequently, wastewater reuse in the European Union remains low, accounting for only 3% of total wastewater volumes (Fabregat, 2025).

A similar pattern can be observed internationally. In the USA, a 2024 policy review reported that 74% of States (37 out of 50) had established intentional regulatory frameworks governing reclaimed water use by November 2023, with all of these states permitting at least some form of agricultural reuse (Thilmany et al., 2024). In Australia, although several advanced potable reuse projects have been successfully implemented, recycled water accounted for only 3% of agricultural irrigation in 2021 (Radcliffe, 2022).

Against this background, this chapter examines the financial and governance mechanisms that may facilitate the development and implementation of circular water projects. In particular, it analyses how circular economy investments differ from conventional water-sector investments (Mbavarira and Grimm, 2021) through the analytical lens of the social acceptability framework proposed by Wüstenhagen et al. (2007).

The analysis focuses primarily on the market dimension of acceptability, examining the willingness of investors, utilities, and firms to adopt circular solutions through financing and governance instruments. To support this analysis, the chapter selectively draws upon the Water Circular Economy Index (WCEI) (Peydayesh and Mezzenga, 2024) and the World Bank's Water in the Circular Economy and Resilience (WICER) framework (Delgado et al., 2024) in order to identify enabling conditions, institutional barriers, and persistent implementation gaps.

Ultimately, the author seeks to provide decision-makers with actionable financial and governance instruments, including tariffs, taxes, transfers, blended finance mechanisms, and green bonds, that may accelerate the transition towards circular water solutions while maintaining principles of equity, sustainability, and economic efficiency.

Stakeholders and decision context

Circular water initiatives vary in scope, ranging from single-utility projects to multi-industry industrial symbiosis. These initiatives involve multiple stakeholders, including investors, water utilities, firms, regulators, municipalities, and end users, each facing distinct incentives and constraints that affect their levels of acceptability. Moreover, these projects often feature unconventional characteristics, including high upfront capital expenditures (CAPEX), extended payback periods, revenue streams that may incorporate non-market elements (e.g. ecosystem services), and regulatory uncertainties (World Bank, 2024). These attributes can diminish private investment potential, often necessitating public funding to substantiate the public benefits generated. Thus, it is essential to identify and classify all project outputs, which may include marketable services capable of generating revenue (e.g. treated water sales, energy, and recovered materials) and public goods (e.g. ecosystem restoration and ecosystem services), thereby justifying public funding (Jiang, 2022).

Despite the novelty of circular projects, the 3T (tariffs, taxes, and transfers) model explained in Barraqué (2020) provides a structured approach: tariffs should aim to cover service costs where practical, taxes can fund public benefits, and transfers (such as grants and concessional financing) can support early-stage implementations. In addition to the 3T model, innovative financial instruments, including blended finance, green bonds, and impact investing, are increasingly utilised to align public objectives with private capital (World Bank, 2016). Effective utilisation of these instruments requires regulatory clarity, standardised impact metrics, and enhanced financial literacy among utilities to develop viable financial propositions.

The adoption and development of circular solutions by utilities and firms depend on their capacity to finance upfront costs, the project's ability to generate revenues, and on tariff structures, regulatory requirements, procurement guidelines, and operational capacity. Utilities with insufficient cost recovery often have limited capacity to finance CAPEX internally, while those in a stronger financial position may invest in circular economy strategies. However, operational and institutional challenges can also impede progress (Enriquez et al., 2020). Key barriers include limited technical capacity for new business models (World Bank, 2019), such as selling recovered nutrients; procurement regulations that favour CAPEX minimisation over lifecycle outcomes; and fragmented responsibilities across sectors (water, agriculture, energy). Utilities that collaborate with firms capable of internalising circular outputs, such as those that use reclaimed water or recovered nutrients, can establish effective partnerships. Nonetheless, implementation requires establishing adequate contractual and quality assurance frameworks, necessitating the involvement of regulatory bodies and government agencies. Good regulatory practice prescribes clarity, stability, and predictability of regulation (Solanes, 2009). In this context, clear regulations regarding reuse standards, sludge quality, and liability allocation are vital for building investor confidence and ensuring public acceptance.

Furthermore, community acceptance is influenced by procedural fairness, transparent communication of risks, and the equitable distribution of costs and benefits (Feldman, 2011).

Economic and governance instruments for circular water solutions

This section outlines key financial and governance mechanisms relevant to circular water solutions, including tariffs, taxes, transfers, blended finance, and bonds. It also discusses governance reforms that facilitate circular investments and emphasises the importance of interventions that enhance the market acceptability and bankability of circular projects, drawing on insights from WCEI and WICER.

Financial mechanisms include the most traditional tariffs and taxes, as well as blended finance, green and blue bonds, and complementary financial instruments. Cost-reflective tariffs are essential for the financial sustainability of utilities and the bankability of circular projects. Tariffs are designed to reflect the lifecycle costs associated with water services, thereby encouraging utilities to invest in practices such as reuse, nutrient and energy recovery, and sludge valorisation. However, ensuring access to water and wastewater services requires setting tariffs at socially and politically acceptable levels, which can hinder the economic sustainability of water utilities. In specific instances, tariffs are designed to reflect the true value of water, accounting for the risk of system failure and sustainability considerations. This raises important questions about the valuation of water and its relationship to the pricing of water services. The Bellagio Principles on Valuing Water establish foundational guidelines that include: (1) recognising the multiple values of water; (2) building trust; (3) protecting all sources; (4) educating to empower; and (5) investing and innovating. The failure to acknowledge the true value of water, coupled with population growth, economic expansion, and shifts in consumption patterns, likely constitutes a primary driver of water misuse and waste (Peydayesh and Mezzenga,

2024; Delgado et al., 2024). In cases where affordability is a concern, targeted social transfers can be implemented as an alternative to general tariff suppression, which can weaken efficiency and investment incentives. It is suggested that regulators balance social tariffs for vulnerable households while ensuring that commercial and industrial users contribute to full cost recovery.

Taxes, on the other hand, can serve as fiscal instruments to reduce effective costs and foster the adoption of circular practices. Possible options include VAT exemptions for circular technologies, tax credits for nutrient or energy recovery, and environmental taxes to internalise environmental costs. These measures can help mitigate economic barriers to implementing circular initiatives.

Blended finance combines concessional public capital, philanthropic support, and commercial financing to help reduce project risks. This approach is especially useful for developing pilot projects that can later be scaled and replicated. Green and blue bonds provide a mechanism for securing long-term capital for large-scale infrastructure projects, including advanced reuse facilities, nutrient recovery plants, and energy-positive treatment works. Successful implementation of these bonds requires robust impact reporting and verification, particularly concerning resource recovery metrics. Additionally, these bonds can help utilities diversify their funding sources and attract investors focused on environmental, social, and governance (ESG) criteria. Finally, complementary financial instruments such as grants and concessional loans can support early-stage projects by covering initial costs and addressing revenue uncertainties. Transfers are particularly critical for decentralised reuse projects, sludge valorisation pilots, and initiatives with significant public benefits, such as basin restoration. However, it is recommended that these transfers be temporary to avoid fostering long-term dependency on public funding, unless clearly justified by the public advantages they generate.

investor risks and safeguard public health while maintaining flexibility to encourage technological innovation. An example of a governance lever is cross-sector governance platforms that align the objectives of utilities, agriculture, industry, and environmental agencies, which are vital for facilitating collaborative projects. Such platforms can lower transaction costs and enable industrial symbiosis, particularly in the context of river basin management, which aligns with WICER's integrated river basin approach. Additionally, procurement guidelines can act as barriers to progress. These guidelines should reward performance through contracts that prioritise outcomes, create predictable revenue streams, and incentivise resource recovery. Furthermore, public-private partnerships and risk-sharing agreements should be designed carefully to leverage private expertise while safeguarding public interests.

BENCHMARKING INSIGHTS AND IMPLICATIONS (WCEI & WICER)

The Water Circular Economy Index (WCEI) and Water in Circular Economy and Resilience (WICER) provide complementary perspectives. The WCEI, as proposed by Peydayesh and Mezzenga (2024), offers cross country benchmarking on water stress, affordability, and service performance. It encapsulates eight indicators that collectively represent the dimensions of the circular economy and reflect the availability of pertinent data globally. These indicators are organised by dimension. Water stress and water affordability (decreasing indicators); water use efficiency, degree of integrated water resource management implementation, and the share of domestic wastewater flows that are adequately treated (optimising indicators); total population with access to safe drinking water, drinking water quality, and the proportion of hydrological basins exhibiting significant changes in surface water extent (retaining indicators).

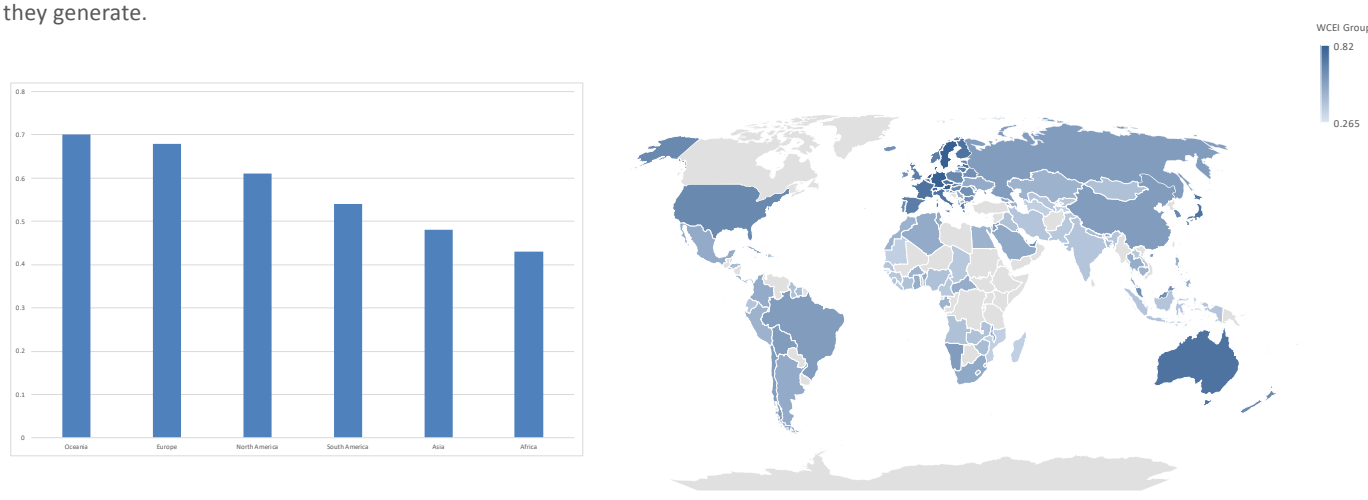


Figure 5.2: WCEI by continent (left) and country (right). Source: Own computation based on Peydayesh and Mezzenga (2024)

To enhance the development and execution of circular economy projects by utilities and firms, regulators and governments are crucial in establishing clear standards for water reuse, sludge quality, and liability allocation. These standards aim to mitigate

Empirical evidence indicates that the continents demonstrating superior performance on the WCEI are Oceania and Europe, followed by North and South America, Asia, and Africa (Figure 5.2a). At the national level, the top five performing countries

are Luxembourg, Switzerland, Singapore, the Netherlands, and Austria, whereas the bottom five include Timor-Leste, Madagascar, Guinea-Bissau, Turkmenistan, and Comoros (Figure 5.2b).

Although the WCEI is a useful benchmarking tool for evaluating the performance of different countries, a more detailed analysis is needed to understand the various contexts involved. Countries with lower WCEI scores often allocate a significant share of their water resources to agricultural use, while those with higher rankings tend to focus more on industrial uses.

The WICER framework (Delgado et al., 2024) provides a practitioner's roadmap for integrating circularity with resilience and inclusivity. It adopts a river basin approach that incorporates resilience, climate mitigation, and inclusivity, while categorising projects based on specific areas of focus. The holistic perspective adopted by the framework necessitates acknowledging the economic value of rivers, lakes, oceans, groundwater, and wetlands. WICER serves as a guide for practitioners to implement circular economy principles in the water sector, particularly in low- and middle-income countries. This framework aims to achieve three primary objectives: delivering resilient and inclusive water services, minimising waste and pollution generated by the sector, and preserving and regenerating natural systems. This approach encompasses not only reuse and recovery but also integrates a holistic river basin perspective that includes resilience, climate mitigation strategies, and inclusiveness.

The integrated analysis of WCEI and WICER offers the following key insights pertinent to finance and governance:

- Tariff cost recovery correlates with circularity readiness: countries with stronger cost recovery are better positioned to finance circular investments.
- Governance maturity predicts uptake: clear mandates and regulatory coherence are consistent enablers of reuse and resource recovery.
- Financing gaps concentrate in sludge valorisation and industrial reuse: these areas face uncertain revenue models and higher perceived risk.
- Blended finance remains underutilised: despite their suitability for de-risking long-payback projects, blended instruments are not yet mainstream in water circularity.
- Data gaps constrain scaling: limited monitoring and standardised reporting hinder performance-based financing and green bond issuance.

These findings imply that policy priorities should focus on strengthening tariff frameworks, clarifying regulations, building institutional platforms, and developing standardised metrics to unlock finance.

Recommendations

The review of literature and policy documents leads to recommendations for utilities, firms, regulators, and environmental agencies.

FINANCIAL RECOMMENDATIONS

1. Reform tariffs to reflect lifecycle costs and enable cost recovery while protecting vulnerable consumers through targeted subsidies.
2. Introduce fiscal incentives (VAT exemptions, tax credits, accelerated depreciation) for circular technologies and resource recovery.
3. Deploy blended finance for pilot and early-stage projects using guarantees and concessional tranches to attract commercial capital.
4. Develop green/blue bond programmes with standardised reporting to finance large-scale reuse and recovery infrastructure.
5. Use transfers strategically to support demonstration projects, capacity building, and projects with strong public good benefits.

GOVERNANCE RECOMMENDATIONS

1. Establish clear reuse and sludge standards and define liability frameworks to reduce regulatory uncertainty.
2. Create cross-sector governance platforms to align mandates for water, agriculture, energy, and the environment at basin and city scales.
3. Adopt outcome-based procurement and performance contracts that reward resource recovery and lifecycle performance.
4. Mandate standardised data and monitoring to support performance-based financing, investor reporting, and green bond verification.
5. Integrate circularity into utility planning and asset management to mainstream resource recovery in investment pipelines.

Conclusions

This paper demonstrates that the transition towards a circular economy within the water sector is progressing unevenly across regions, reflecting differences in regulatory frameworks, financing mechanisms, institutional capacity, and levels of social and market acceptance. Several persistent barriers continue to constrain the broader adoption of circular practices, including rigid tariff structures, insufficient financial literacy among sector stakeholders, limited regulatory clarity, and institutional inertia.

The analysis further highlights that successful transitions towards circular water systems depend on the alignment of regulatory reform, innovative financing instruments, and effective knowledge transfer across utilities, firms, and financial actors. In this context, benchmarking tools such as the Water Circular Economy Index (WCEI) can play a significant role in monitoring progress, facilitating comparative analysis, and supporting the dissemination of best practices across jurisdictions.

The findings also suggest that enhancing the acceptability of circular water initiatives requires stronger coordination among policymakers, utilities, investors, firms, and consumers. Such collaboration should prioritise resilience, inclusivity, environmental sustainability, and long-term value creation. Ultimately, advancing circularity in the water sector will require integrated governance approaches capable of balancing economic viability, social equity, and ecological protection.

References

Barraqué, B. (2020). Full cost recovery of water services and the 3 T's of OECD. *Utilities Policy*, 62, 100981.

Delgado, A., Rodriguez, D. J., Amadei, C. A., & Makino, M. (2024). Water in the circular economy and resilience (WICER) framework. *Utilities Policy*, 87, 101604.

Enriquez, S., Sánchez Triana, E., & Guerra López, M. G. (2020). Economic instruments and financial mechanisms for the adoption of a circular economy. In *An Introduction to Circular Economy* (pp. 455–482). Springer.

European Parliament (2020). REGULATION (EU) 2020/741 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on minimum requirements for water reuse. https://eur-lex.europa.eu/eli/reg/2020/741/oj/eng

Fabregat, V. (2025). Unlocking the potential of reclaimed water: analysis of the challenges and market size as a strategic solution for water scarcity in europe. *Challenges*, 16(3), 43.

Feldman, D. L. (2011). Integrated water management and environmental justice–public acceptability and fairness in adopting water innovations. *Water Science and Technology: Water Supply*, 11(2), 135–141.

Jiang, X. (2022). Financing water infrastructure: public and private approaches. *Journal of Water Finance*, 12(3), 45–62.

Mclennan, C., Rudi, G., Altchenko, Y., & Ait-Mouheb, N. (2024). Will the European Regulation for water reuse for agricultural irrigation foster this practice in the European Union? *Water Reuse,* 14(2), 115–135.

Mbavarira, T. M., & Grimm, C. (2021). A systemic view on circular economy in the water industry: learnings from a Belgian and Dutch case. *Sustainability*, 13(6), 3313.

Peydayesh, M., & Mezzenga, R. (2024). The circular economy of water across the six continents. *Chemical Society Reviews*, 53(9), 4333–4348.

Radcliffe, J. C. (2022). Current status of recycled water for agricultural irrigation in Australia, potential opportunities, and emerging areas of concern. *Science of the Total Environment*, 807, 151676.

Solanes, M. (2009). Common Regulatory Principles and Regulation of Water and Sanitation Services. International Institute for Sustainable Development (IISD). https://www.iisd.org/system/files/publications/water_and_sanitation.pdf

Thilmany, E. A., Newton, S., Goeringer, P., & Rosenberg Goldstein, R. E. (2024). Reclaimed water use regulations in the US: Evaluating changes and regional patterns in patchwork state policies from 2004–2023. *Water*, 16(2), 334.

Tolliver, C., Keeley, A. R., & Managi, S. (2019). Green bonds for the Paris Agreement and sustainable development goals. *Environmental Research Letters*, 14(6), 064009.

World Bank. (2016). *Financing options for the 2030 water agenda* (Knowledge brief). World Bank. https://openknowledge.worldbank.org/server/api/core/bitstreams/b3c99116-be36-5fa5-991b-390e62856dca/content

World Bank (2024). *Making the economic and financial case for circular projects in water*. The World Bank, Washington, DC. https://thedocs.worldbank.org/en/doc/553c323db2132d2ee349da34a88a388b-0320082024/original/2024-03-06-WICER-Economic-and-Financial.pdf

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy, 35(5), 2683–2691.

| 5.3 |

Clean water scarcity: a multidimensional challenge

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Water security can no longer be reduced to a question of quantity alone. A purely volumetric assessment (e.g. Damkjaer & Taylor, 2017) provides an incomplete picture of the challenges we face. Factoring the three interacting dimensions availability, quality, and usability into scarcity assessment, a much more complex situation is formed.

Water quality degradation is increasingly recognised as a critical driver of scarcity as much as physical shortages. This means that even in areas with abundant water, pollution can render it unusable for drinking, agriculture, or industrial purposes. The consequences are already visible: over 55% of the global population experiences clean water scarcity for at least one month each year, a figure that could rise to 66% by 2100 if current trends continue (Jones et al., 2023).

Yet, the problem extends beyond quality. Clean water scarcity is deeply tied to economic water scarcity, for instance, water is physically available but cannot be accessed due to financial, infrastructural, or institutional barriers (World Bank, 2025). This primarily affects socio-economically weak regions (e.g. in Sub-Saharan Africa (UNICEF, 2025)), making them more vulnerable to exacerbated water scarcity.

The solution lies in adopting a multidimensional approach that integrates blue water scarcity (surface and groundwater shortages), green water scarcity (soil moisture deficits affecting rainfed plant growth), and clean water scarcity (pollution-driven unusability) (Liu et al., 2025). These dimensions are interconnected and need to be considered mutually for a complete and realistic water scarcity assessment and effective management.

Water does not exist in a vacuum; it is deeply linked to energy production, food security, and ecological health. For example, agriculture consumes roughly 70% of global freshwater resources, making it both a major driver and a potential victim of water scarcity. Similarly, energy systems – particularly hydropower and cooling for thermal plants – depend on reliable and clean water supplies.

Climate change further complicates this picture. Extended droughts and storm events, elevated temperatures, increased evaporation rates, and diminished snowpacks collectively alter hydrological regimes – both temporally and volumetrically – typically resulting in reduced availability of freshwater resources (Ravinandrasana and Franzke, 2025). These changes do not affect regions uniformly; some may see improvements in water availability, while others face worsening scarcity.

Siloed and fragmented approaches across administrative sectors and national boundaries, coupled with disjointed regulatory thresholds and static assessment metrics, fail to capture the dynamic and interconnected nature of water systems. Harmonised monitoring, assessment, and management frameworks – ultimately aligned with trade and finance policies – could represent a central prerequisite for achieving the Sustainable Development Goals (Malagó et al. 2021, UNESCO 2024).

Dynamic, spatially explicit models can help accounting for variability, legacy effects, and the cascading impacts of water scarcity across regions and sectors (Yang et al., 2024). Nature-based solutions, such as wetlands, offer a promising path forward. These systems can simultaneously store water, filter pollutants, and restore ecosystems, providing multiple benefits that align with climate resilience and biodiversity goals (EU-COM, 2023; IPBES, 2019; KME, 2025; UNEP, 2024).

The message is clear: clean water scarcity is a multidimensional challenge, and solving it requires a holistic approach that reflects the full complexity of water systems and their inter-sectoral connections. Only by integrating these dimensions can we develop credible, resilient, and equitable water security strategies for the future.

References

Damkjaer, S., & Taylor, R. (2017). The measurement of water scarcity: Defining a meaningful indicator. *Ambio*, 46(5), 513–531.

EU-COM. (2023). *EU Nature Restoration Law: Restoring Europe's degraded ecosystems by 2050*. Brussels: EC Environment Directorate-General.

Hoff, H. (2011). *Understanding the Nexus. Background paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus*. Stockholm Environment Institute. https://www.sei.org/publications/understanding-the-nexus/

IPBES. (2019). *Global Assessment Report on Biodiversity and Ecosystem Services.* Bonn: Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services.

Jones, E. R., Bierkens, M. F. P., van Puijenbroek, P. J. T. M., van Beek, L. P. H., Wanders, N., Sutanudjaja, E. H., & van Vliet, M. T. H. (2023). Sub Saharan Africa will increasingly become the dominant hotspot of surface water pollution. *Nature Water*, 1, 602–613. https://doi.org/10.1038/s44221-023-00105-5

KME (Korean Ministry of Environment). (2025). *The 4th Comprehensive Plan for Non-point Source Pollution Management (2025–2030)*. Seoul: ME.

Liu, W., Fu, Z., van Vliet, M.T., Davis, K.F., Ciais, P., Bao, Y., Bai, Y., Du, T., Kang, S., Yin, Z., & Fang, Y. (2025). Global overlooked multidimensional water scarcity. *Proceedings of the National Academy of Sciences*, 122(26), e2413541122. https://www.pnas.org/doi/10.1073/pnas.2413541122

Malagó, A., Comero, S., Bouraoui, F., Kazezyilmaz Alhan, C. M., Gawlik, B. M., Easton, P., & Laspidou, C. (2021). An analytical framework to assess SDG targets within the context of WEFE nexus in the Mediterranean region. *Resources, Conservation & Recycling*, 164, 105205.

Ravinandrasana, V. P., & Franzke, C. L. (2025). The first emergence of unprecedented global water scarcity in the Anthropocene. *Nature Communications*, 16(1), 8281.

UNEP (United Nations Environment Programme). (2024). *Global water shortages are looming. Here is what can be done about them*. https://www.unep.org/news-and-stories/story/global-water-shortages-are-looming-here-what-can-be-done-about-them

UNESCO. (2024). Statistics | *UN World Water Development Report*. Retrieved October 30, 2025, from https://unesco.org/reports/wwdr/en/2024/s

UNICEF. (2025). *Water scarcity*. Retrieved from https://www.unicef.org/wash/water-scarcity

World Bank. (2025). *Water Overview: Development news, research, data*. https://www.worldbank.org/en/topic/water/overview

Yang, J., Li, J., van Vliet, M. T. H., Jones, E. R., Huang, Z., Liu, M., & Bi, J. (2024). Economic risks hidden in local water pollution and global markets: A retrospective analysis (1995–2010) and future perspectives on SDG 6. *Water Research*, 252, 121216. https://doi.org/10.1016/j.watres.2024.121216

| 5.4 |

Building ripples of change: connecting water quality, youth engagement and governance innovation

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Introduction

Across the world, water systems are under increasing strain from climate change (Szinai et al., 2024), population growth, and accelerating urbanisation, while inequities in access and participation in governance continue to intensify (Keeler et al., 2020). Many communities remain excluded from decision-making processes that directly affect their water security (Adeyeye et al., 2020). Governance structures often struggle to balance technical innovation with social inclusion. These challenges emphasise a growing realisation that progress toward Sustainable Development Goal 6: Clean Water and Sanitation depends not only on technical innovation, but also on inclusive governance, community participation, and local capacity building.

International networks such as the International Water Association (IWA) have increasingly recognised that the future of water governance requires new models of collaboration that include diverse players; especially youth and early-career professionals. However, youth engagement is often limited to awareness campaigns or consultation, rather than meaningful participation in project design, implementation, and decision-making.

This chapter presents FLOW RIPPLE, a youth-led framework developed through the IWA's Leadership Programme (LeaP) to connect water quality education, community-based action, and participatory governance. Drawing from cross-country collaboration, interviews, a literature review, and pilot workshops in Thailand and China, the article highlights how structured youth engagement can support more inclusive, adaptive, and locally grounded water governance.

Key terminology

FLOW RIPPLE (Future Leaders of Water Raising Impact through People, Projects, Leadership, and Education): A youth-led framework developed through the International Water Association's Leadership Programme (LeaP) that guides communities and young professionals in co-designing solutions to local water challenges. It emphasises participatory governance, systems thinking, and cross-sector collaboration to link technical innovation with social inclusion.

CBWTS (community-based water treatment solutions): An approach that integrates simple, locally adaptable water treatment technologies with community participation and capacity building.

SDGs (Sustainable Development Goals): A global set of goals adopted by the United Nations in 2015 to guide progress on social, environmental, and economic sustainability by 2030.

Building the FLOW RIPPLE Movement

FLOW RIPPLE was first developed as a participatory framework to explore how youth and communities can co-create solutions to address local water challenges. Rather than presenting youth as passive beneficiaries, the framework positions them as facilitators, translators, and collaborators who can connect technical water quality knowledge with local priorities. Through pilot workshops and continued collaboration, FLOW RIPPLE has since evolved into a broader youth-led initiative focused on education, participatory governance, and community-based water action.

Developing the framework

The framework was developed by young water professionals from Thailand, China, Canada, and the USA through LeaP. The team integrated perspectives from engineering, governance, and community engagement to explore how youth can contribute meaningfully to local water governance.

The team conducted informal interviews and consultations with young professionals experienced in community-based water and sanitation projects. Across regions, several common themes emerged: successful projects require trust-building, local technical capacity, inclusive participation, and sustained institutional support (Table 5.1). Participants also noted recurring barriers, including regulatory complexity, limited funding, and difficulty maintaining engagement after initial implementation. These insights reinforced the need for a practical framework that moves youth participation beyond awareness-raising towards shared leadership in design, decision-making, and local capacity development.

The group also reviewed existing participatory frameworks from organisations such as UNESCO (Imburgia et al., 2025), the United Nations (United Nations, 2022), and the World Health Organization (WHO, 2024), particularly those focused on water quality guidelines, community-based water management, and youth engagement in the water sector (UNESCO, 2019; United Nations, 2018). Together, the interviews and literature review formed the foundation for designing a framework that merges technical problem-solving with community empowerment.

To validate and further refine the framework, online workshops were held with youth groups and university partners. The sessions served both as training and feedback opportunities. Participant feedback led to clearer language for non-technical audiences, stronger emphasis on collaboration with local institutions, and more practical examples of how the framework could be applied in different community settings.

The Seven Ripples of Change within the FLOW RIPPLE framework

The framework is organised around seven ripples that guide youth and communities from identifying local water quality challenges to implementing solutions and sharing lessons. Each ripple connects technical understanding with participation, helping communities move from awareness to coordinated action.

1. Defining the problem and objectives: Identifies local water quality challenges, affected communities, and shared priorities for action. Establishing clear objectives early helps ensure that solutions respond to real community needs rather than assumed problems.

2. Engaging stakeholders: Brings together youth, community members, technical experts, and local authorities to align goals and responsibilities. Early engagement builds trust, legitimacy, and accountability for implementation.

3. Identifying pollution sources and contaminant concentrations: Uses monitoring, literature review, and local knowledge to understand contaminants, pollution sources, and priority risks. Combining scientific evidence with community insight supports transparent and locally relevant decision-making.

4. Selecting treatment strategies and community solutions: Evaluates feasible, affordable, and locally appropriate treatment or management options. Considering cost, maintenance, and community acceptance helps ensure selected solutions can be sustained.

5. Planning for change: from ideas to action: Translates proposed solutions into timelines, resource needs, partnerships, and implementation plans. It bridges technical planning with social coordination so ideas can move toward action.

Table 5.1 Insights from interviews with young professionals on community-based water initiatives

Region / role	Focus area	Key insights	Implications for the FLOW RIPPLE framework
Europe / Start up CEO	Community adoption of modern technologies	Regulatory documentation and administrative requirements can discourage participation; community trust and perception shape project success.	Simplify engagement processes and integrate cultural considerations when introducing modern technologies.
East Africa / Water Access Programme Manager	Rural water access and maintenance	Local technicians sustain systems; communities are eager to learn and invest in convenient access to clean water.	Highlight local capacity building and technical training as pillars for sustainability.
South America / PhD student	Stakeholder engagement and citizen science	Visual communication tools and small incentives help maintain community participation, especially in areas with limited connectivity.	Strengthen educational materials with visual aids and adaptable outreach strategies.
South Asia / Project Engineer	Gender inclusion and advocacy	Involving women and identifying target groups broadens outreach and ensures equity in monitoring and education efforts.	Integrate gender-responsive design and inclusive advocacy pathways into the framework.

6. Taking action and tracking progress: Focuses on implementation, monitoring, and feedback. Tracking progress allows communities to adapt, strengthen accountability, and improve long-term outcomes.
7. Sharing knowledge and building movements: Shares lessons through peer learning, community forums, and broader platforms. This helps sustain momentum, build youth leadership, and inspire new collaboration.

The application of the framework was subsequently evaluated through pilot activities and training workshops with youth and university partners. These pilots demonstrated how the Seven Ripples of Change can be adapted to real-world contexts, serving as both a learning tool and a governance mechanism. The following section presents insights from these pilot studies.

Case study: pilot workshops in Thailand and China

Over 2.2 billion people worldwide lack access to safely managed drinking water services, with more than half residing in Asia (Li et al., 2025; Wang et al., 2022). To explore the framework's application in different regional contexts, pilot workshops were conducted with university partners in Thailand and China. Participants aged 18–22 were recruited from King Mongkut's University of Technology Thonburi in Thailand and the Harbin Institute of Technology in China.

The workshops introduced participants to the FLOW RIPPLE framework and its application to CBWTS. Pre- and post-workshop assessments using a 10-point questionnaire were used to evaluate changes in understanding of CBWTS, the framework, and the role of youth in addressing water pollution.

Findings revealed substantial learning gains. As shown in Figure 5.3a, participant understanding of CBWTS increased by 39% following the workshop, while awareness of the role of youth in addressing water pollution rose by 30%. Participants in both Bangkok and Harbin showed similar improvement trends, suggesting that the framework can be adapted across cultural and institutional contexts. Post-workshop evaluations also showed strong satisfaction, with mean scores ranging from 8.2 to 9.2 out of 10 (Figure 5.3b). The highest score was recorded for the statement that the workshop helped participants understand how to use the framework.

These results suggest that the framework can serve as both an educational tool and a governance-oriented approach, fostering youth leadership, technical understanding, and community collaboration in diverse contexts.

Findings from the pilot workshops reveal broader implications for the global water community. The results demonstrate how the framework can be applied beyond its pilot regions to strengthen youth engagement, enhance local collaboration, and inform more inclusive governance practices. These insights highlight opportunities for the water sector to embed participatory approaches into ongoing programmes, policies, and institutional frameworks.

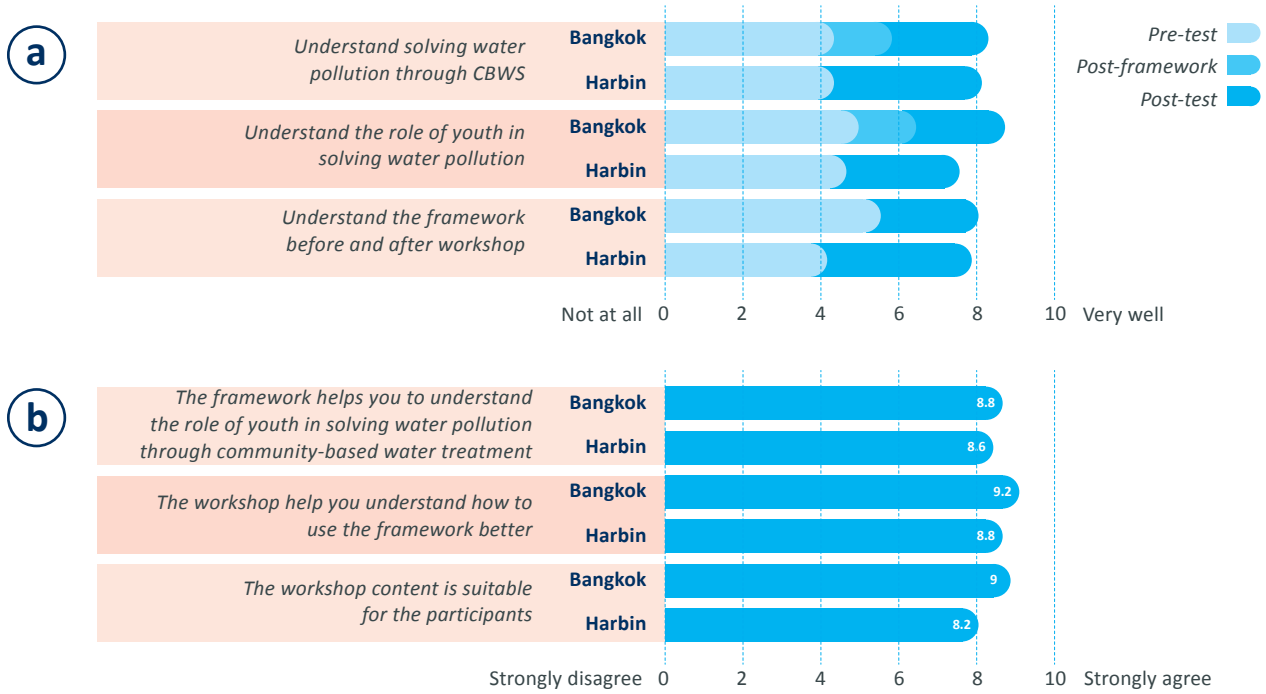


Figure 5.3: Participant learning gains and workshop feedback. (a) Changes in understanding of CBWTS, the framework, and the role of youth before and after framework review and workshop participation. (b) Participant agreement that the framework and workshop supported their understanding.

Implications for the water sector

The FLOW RIPPLE framework demonstrates how youth-led co-creation can support more inclusive and adaptive water governance. Its pilot application suggests several opportunities for the broader water sector to strengthen participation, equity, and local ownership in water management.

Water quality challenges vary by region, governance structure, and community need. FLOW RIPPLE can be tailored by water agencies, universities, non-governmental organisations (NGOs), and youth organisations to reflect local contamination issues, available resources, and institutional conditions.

Participatory approaches are strongest when they include continuous learning. Peer exchange, mentorship, monitoring, and community feedback can help improve implementation, strengthen accountability, and support long-term engagement.

Although the pilots were conducted in Asia, the framework can be adapted in other regions seeking to strengthen youth engagement and community-based water action. Partnerships with utilities, universities, NGOs, youth organisations, and international networks can help expand its application while keeping implementation locally grounded.

The Seven Ripples of Change also connect local water quality action with broader governance functions, including evidence gathering, stakeholder inclusion, decision-making, implementation, capacity building, and partnerships. These functions align with several SDGs (Table 5.2).

Table 5.2 Alignment of the FLOW RIPPLE Framework with Governance Functions and SDG Targets

Ripple	Governance function	Related SDG target
1. Defining the problem	Evidence gathering and agenda setting	SDG 6.1, 6.3
2. Engaging stakeholders	Collaboration and inclusion	SDG 17.17
3. Identifying pollution sources and contaminants	Knowledge integration and transparency	SDG 6.3
4. Selecting treatment strategies	Decision-making and innovation in infrastructure	SDG 9.4
5. Planning for change	Policy alignment and resource planning	SDG 11.3
6. Taking action and tracking progress	Implementation, cooperation, and capacity building	SDG 6.a
7. Sharing knowledge and building movements	Capacity building, partnerships, and climate resilience	SDG 13.3, 17.16

Conclusion

The framework demonstrates how youth-led co-creation can transform participation into meaningful contributions to water governance. By linking CBWTS concepts with collaborative learning and local decision-making, the framework offers a practical structure for addressing water quality challenges while strengthening inclusion, capacity, and accountability.

Pilot applications in Thailand and China suggest that when youth are equipped with knowledge, mentorship, and platforms for co-design, they can translate awareness into locally relevant action. The framework is not intended to replace existing governance systems, but to complement them by creating clearer pathways for youth, communities, and institutions to work together.

As water systems face increasing climate, demographic, and equity pressures, technical solutions alone will not be sufficient. The future of water governance will also depend on people who can connect science, policy, and community action. FLOW RIPPLE offers one model for building that connection.

References

Adeyeye, K., Gibberd, J., & Chakwizira, J. (2020). Water marginality in rural and peri-urban communities. *Journal of Cleaner Production*, 273, 122594. https://doi.org/10.1016/j.jclepro.2020.122594

Guidelines for drinking-water quality: Small water supplies. (2024). World Health Organization.

Imburgia, L., Fusi, A., Shiwangni, S., Hoyte, W. S., & Thuy, L. (2025). *The Interconnected Nature of Water, Gender and Climate Case Studies from the Pacific Small Island Developing States*. https://unesdoc.unesco.org/ark:/48223/pf0000392395

Keeler, B. L., Derickson, K. D., Waters, H., & Walker, R. (2020). Advancing water equity demands new approaches to sustainability science. *One Earth*, 2(3), 211–213. https://doi.org/10.1016/j.oneear.2020.03.003

Li, N., Gao, W., Yan, B., Cheng, Z., Chen, G., & Ok, Y. S. (2025). Enhancing advanced oxidation processes: The role of AI in heterogeneous catalysis. *Science Bulletin*, 70(6), 811–814. https://doi.org/10.1016/j.scib.2025.01.022

Szinai, J. K., Yates, D., Sánchez-Pérez, P. A., Staadecker, M., Kammen, D. M., Jones, A. D., & Hidalgo-Gonzalez, P. (2024). Climate change and its influence on water systems increases the cost of electricity system decarbonization. *Nature Communications*, 15(1), 10050. https://doi.org/10.1038/s41467-024-54162-9

UNESCO. (2019). World Youth Report 2018: Youth and the 2030 *Agenda for Sustainable Development*. UN. https://doi.org/10.18356/0c6f53e0-en

United Nations. (2018, March 12). *Youth and the Integrated Management of Water Resources*. United Nations; United Nations. https://www.un.org/en/chronicle/article/youth-and-integrated-management-water-resources

United Nations. (2022). *Environmental Policy for Peacekeeping Operations and Field-Based Special Political Missions* (No. REF. NO: DOS/2022.01). https://operationalsupport.un.org/sites/default/files/dos_2022.01_environmental_policy_for_peackeeping_operations_and_special_political_missions.pdf

Wang, X., Chen, Y., Fang, G., Li, Z., & Liu, Y. (2022). The growing water crisis in Central Asia and the driving forces behind it. *Journal of Cleaner Production*, 378, 134574. https://doi.org/10.1016/j.jclepro.2022.134574

| 5.5 |

Summary of the state of investment in nature-based solutions for water security

Authors: *Brooke Atwell, Mia Smith, and Gena Gammie on behalf of the Nature-based Solutions for Climate-resilient Water and Sanitation Management Cluster*

Introduction

Doubling down on nature: State of investment in nature-based solutions for water security, 2025 (Smith et al., 2025), co-published by Forest Trends and The Nature Conservancy, is the most comprehensive global assessment to date of finance explicitly directed toward nature-based solutions (NbS) with water-related objectives, such as mitigating flood risk, improving water quality, and securing supply. This report tracks global investments in NbS for water security from 2013 to 2023, and includes 1,645 programmes and projects – referred to collectively as "initiatives" – across 140 countries that implemented on-the-ground interventions in terrestrial, freshwater, or brackish ecosystems with explicit water security objectives.

Among other findings, the data show that investment in NbS for water security is growing steadily around the world. In fact, global investments in NbS for water security have doubled over the past decade, reaching USD 49 billion (B) in 2023. The new report tracks where finance for these investments are *actually* flowing, including who is investing, what's driving growth, and what barriers to scaling remain. Compiled from hundreds of sources globally, including public databases, government reports, survey submissions, and expert interviews, the report shows a growing confidence in nature's capacity to safeguard freshwater resources and bolster climate adaptation.

Key terminology

Nature-based solutions (NbS) are "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN 2016).

Public incentives for landholders may be an aspect of large programmes typically operating at national or supranational scales that primarily pay farmers and other landholders to improve land management practices for conservation outcomes with water benefits.

Other public good investments in watersheds include public natural infrastructure projects that may not provide a direct benefit to payers, but rather, generate a greater public good. These include grants to farmers and community groups and projects funded by foreign assistance and multilaterals. They are typically implemented through projects at the national or regional scale.

User-driven watershed investments channel funds from water users or infrastructure managers – such as water utilities, companies, or cities – to landholders or other parties to support watershed conservation, restoration, or management. Resources can be channelled directly or through intermediary platforms, like a water fund or public agency. In contrast with the prior category, the motivation for these investments tends to be to manage water risks that directly affect the operations of the payer, and these investments tend to occur at the local or watershed scale.

Water quality trading and offset markets are mechanisms that enable water users to meet regulatory or sustainability targets by funding offsite actions, typically by other land or water users, that improve water quality. These improvements are quantified into credits or similar units, which are exchanged within a defined watershed-based market. Most trading mechanisms are driven by regulatory compliance, though some operate on a voluntary basis.

Environmental water markets are mechanisms that facilitate the purchase or leasing of water rights to sustain freshwater ecosystems and their functions. Typically, a public good provider such as a government or foundation will acquire rights in order to prevent the water from being extracted.

Key insights

Global trends

In 2023, global investment in NbS for water security reached at least USD 49 billion (B), marking a two-fold increase in investment since 2013 (Figure 5.4). Around the world, governments, utilities, companies, civil society, and local land users are increasingly understanding the value nature provides to managing water-related risks like floods, scarcity, and contamination. This growing awareness is driving greater funding and tangible action to protect, restore, and manage the ecosystems that are essential for water security.

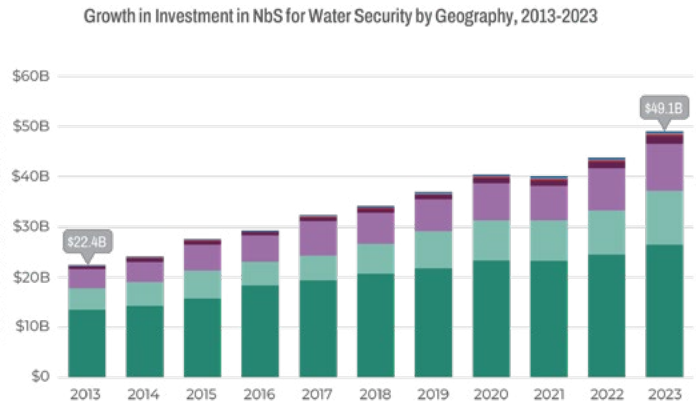


Figure 5.4: Growth in investment in NbS for water security by geography, 2013-2023. Source: Smith et al. (2025).

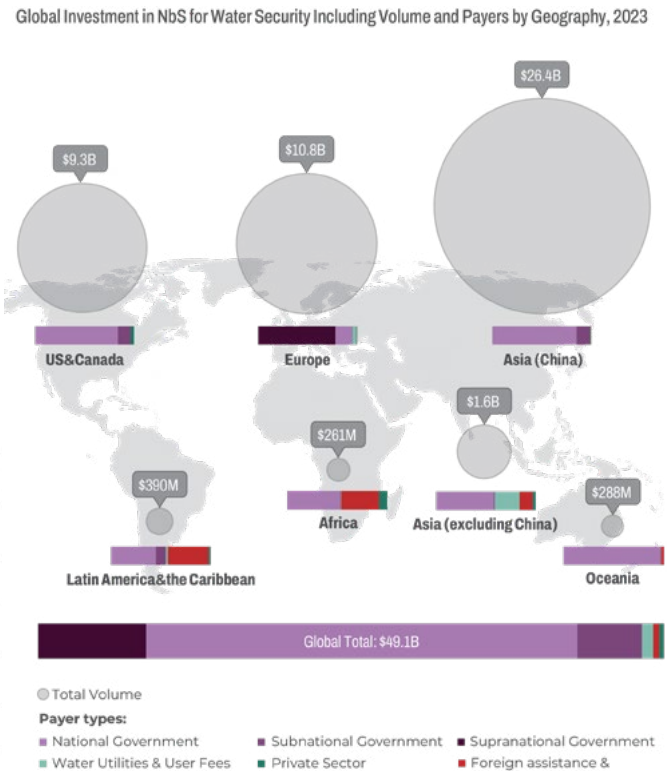


Figure 5.5: Global investment in NbS for water security including volume and payers by geography, 2023. Source: Smith et al. (2025).

China, the USA, and the EU dominate the landscape, accounting for 94% of total investment (Figure 5.5). China alone contributed USD 26.4B (54%). Outside of the "Big Three," investment is growing at a faster rate, especially in Africa (5.1× growth over 10 years) and Oceania (3.4×). The top water risk addressed globally is flooding, followed by water quality issues. Scarcity was a primary concern in Africa and Latin America.

Additional regional trends are presented in the full report (Smith et al., 2025, p. 37).

Investment by payer type and mechanism

While the full report Smith et al. (2025) delves into all payers & mechanisms in more detail, this summary will focus on water user fees and user-driven watershed investments which capture investments made by water users – including water utilities.

PAYER TYPES

Investments in NbS for water are dominated by governments investing domestically (USD 47.4B, and 97% of all investment), the bulk of which come from national governments (USD 33.8B). Subnational government investment (USD 5.1B) includes investments by regional (84%) and local (16%) governments. Peru, for example, showed notable growth starting in 2015 due to changes in its public investment system, including regulations that explicitly recognise natural infrastructure as infrastructure (Benites and Gammie 2022).

Investments by other actors – including public and private utilities, foreign assistance and multilateral institutions, and the private sector – make up a small percentage of overall investment but are growing at faster rates (Table 5.3).

Direct investments through non-repayable instruments by foreign assistance and multilateral institutions have increased 10-fold over the last decade, reaching USD 489 million (M) in 2023. While most of these investments targeted Asia, the fastest growth took place in Latin America and the Caribbean. The private sector is the fastest growing segment in our dataset, increasing over 30-fold over the last decade to reach USD 345M in 2023. Despite this rapid growth, it still represents less than 1% of global investment in NbS for water. More than two-thirds of private investment in 2023 was driven by regulation.

Investments funded by water user fees have grown 3.4-fold over the past decade, reaching at least USD 867M (2% of all investment) in 2023. These investments, which are usually managed by water utilities or public agencies, grew faster than investments by governments (Table 5.3). Notable examples of investments by water users managed by public agencies include:

- France's six water agencies, which have been investing user fees in restoration efforts using NbS since 2018. Together, they invested an estimated USD 446M in 2023.
- In South Korea, water-user fees fund four river basin management funds (established 1998–2000), which together invested an estimated USD 268M in 2023.
- Vietnam's Payment for Ecosystem Services Program (established 2008), funded by various water users (primarily hydropower production facilities), invested an estimated USD 115M in 2023.
- In Colombia, fees on water users have been collected since 1993 and are used to cover water resource management, including an estimated USD 3.3M for the protection and restoration of water resources in national parks and conservation areas in 2023. These fees are set by the Ministry of Environment and Sustainable Development and collected by regional and municipal environmental authorities.

Other countries, such as the USA, Japan, the UK, Ecuador, and Peru, saw growing involvement by water utilities. In Peru, 43 of the country's 50 public water utilities have begun to implement initiatives to invest in their basin headwaters, including the use of Indigenous practices for groundwater recharge (SUNASS 2022). Emerging initiatives, like Australian water utility Coliban Water's efforts to improve the health of the Coliban River, reflect utilities' growing role in driving localised NbS initiatives.

Table 5.3 Growth in investment in NbS for water security, by payer type, 2013–2023. Source: Smith et al. (2025).

	Payer Type						
	Government			Water Utilities (public & private) & user fees	Foreign assistance & multilateral institutions	Private Sector	Grand Total
	Supra-national	National	Sub-national				
2013	4.2B	15.4B	2.3B	253M	47M	9.3M	22.3B
2023	8.5B	33.8B	5.1B	867M	489M	345M	49.1B
% of Global (2023)	17%	69%	10%	2%	1%	0.7%	100%
Rate of Growth (2013-2023)	2.0x	2.2x	2.2x	3.4x	10x	37x	2.2x

MECHANISMS

The report categorises NbS investment into five mechanisms: public incentives for landholders, other public investments for a public good, user-driven watershed investments, water quality trading and offsets, and environmental water markets (Figure 5.6).

Almost half of the total investment volume in NbS for water in 2023 was through **public incentives for landholders** (USD 23.4B), which pay farmers, foresters, and other landholders to improve land management practices for conservation outcomes with water benefits, usually on a voluntary basis. These initiatives are typically large, publicly funded programmes operating at national or supranational (in the case of the EU) scales.

Other investments for a public good (USD 23.7B) was the fastest growing mechanism type (3.3-fold) and included over 600 different initiatives funded by supranational, national, and subnational governments as well as bilateral foreign assistance agencies and multilateral institutions. Unlike landholder incentives, these investments tend to involve smaller initiatives averaging USD 39M each, and often emphasise local interventions and adaptability, leading to a higher diversity of designs.

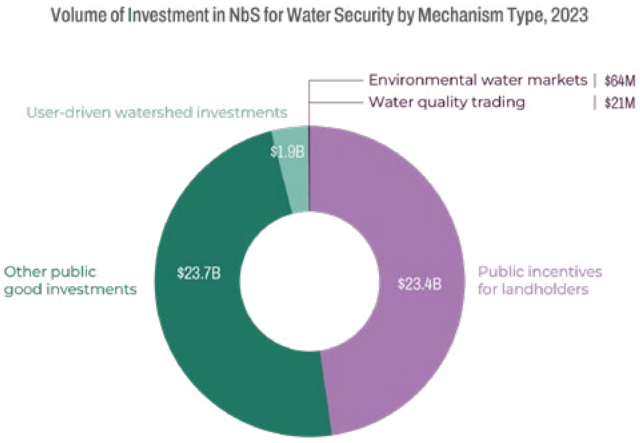


Figure 5.6: Volume of investment in NbS for water security by mechanism type, 2023. Source: Smith et al. (2025).

Water quality trading markets allow water users to purchase credits generated by practices that reduce water pollution or improve water quality, and are driven, in most cases, by regulations limiting water pollutants. In 2023, these programmes transacted at least USD 21M in credits. Environmental water markets channelled USD 64M in funding for NbS for water in 2023. This includes initiatives that act in the public interest by buying or leasing water rights, which are

set aside to ensure minimum water levels to protect aquatic habitats or recharge groundwater. Water markets show limited adoption outside of the USA and Australia.

User-driven watershed investments, i.e. investments by the direct beneficiaries of watershed services, channelled nearly USD 2B in 2023. This includes investments funded by water user fees (USD 867M), user-driven investments by subnational governments (USD 881M), and companies and foundations (USD 105M).

The average value channelled by user-driven initiatives in 2023 was USD 8.2M, which is two orders of magnitude smaller than the average value of landholder incentive programmes for NbS. Most of the investment volume was implemented bilaterally, but at least USD 407M was implemented through collective action vehicles such as water funds. Water funds are financial and governance mechanisms that unite public, private, and civil society to improve water security by investing in NbS. The Greater Cape Town Water Fund (established in 2017) is one such collective action vehicle involving non-governmental organisations (NGOs), private companies, and government entities including the City of Cape Town, National Department of Water and Sanitation, National Department of Environmental Affairs, and Provincial Department of Environmental Affairs and Development Planning. The water fund prioritises and coordinates implementation across stakeholders and trains and employs high-angle technicians to remove invasive pine trees in the catchment, returning 55B litres of water to the system, equivalent to two months of water supply for the city of Cape Town (Stafford et al. 2018).

User-driven investments in NbS for water by subnational governments have grown 2.5-fold over the last decade. Some notable examples include:

- China's eco-compensation programmes at the municipal level (USD 660M), as well as horizontal programmes that managed watersheds between provinces (USD 123M) (Smith et al., 2025, p. 43), transfer payments from one province to another to co-manage shared watersheds, evolving a mechanism that started off as a top-down approach driven by national government to one driven by beneficiaries of watershed services.
- In the USA, the New York City Department of Environmental Protection invests in the Catskill watershed, while the City of San Antonio invests in the protection of the Edwards aquifer. The San Antonio programme was first funded through a sales tax, and later through a line item in the public budget. Additionally, hundreds of local governments in the USA contribute matching funds to the US Forest Service's Source Water Protection Program to support forest management in local watersheds.
- In Japan, the Tokyo Metropolitan Government and Yokohama City Waterworks Bureau are both investing in the conservation of forests upstream of the rivers that provide water to urban residents.
- In Ecuador, the municipalities of Cuenca and San Pedro de Pimampiro both have their own watershed investment programmes, while municipalities in Loja and neighboring provinces contribute to the FORAGUA water fund.

These user-driven investments have important differences by geography (Figure 5.5). Investments by utilities dominate in Europe, Oceania, and Asia outside of China. Investments by subnational governments play a dominant role in China, while the private sector leads user-driven investments in Africa.

Recommendations

Based on the report findings and their own experience, a group of experts and practitioners in the field developed recommendations to diversify and accelerate investment in NbS for water security. In summary, these are:

1. **Build reliable and resilient revenue models:** Predictable, long-term funding is essential – particularly given rising risks to centralised public funding for NbS. While the scale of national funding will not be replaced by other payers in the short term, models that draw on direct beneficiaries of NbS, such as water users or property owners, show the greatest promise for durability and growth.
2. **Strengthen policy and planning for long-term impact:** Upstream policies and planning frameworks shape the feasibility and quality of NbS investments. Integrated strategies are critical to embed NbS into national infrastructure, biodiversity, water, disaster risk reduction, and other related agendas, finding synergy across sectors and ecosystem services, and attracting new partnerships.
3. **Grow and steer private investment to highest-value use:** The private sector currently accounts for less than 1% of global investment in NbS for water security. While it won't replace public funding, private investment can play a catalytic role when strategically aligned, and public partners can help shape the enabling environment to channel this investment toward scalable, high-impact solutions.
4. **Strengthen the NbS delivery system and evidence base to scale impact:** Scaling investment in NbS for water security requires not just more funding, but a stronger delivery ecosystem – grounded in skilled professionals, trusted data, and compelling evidence of impact.
5. **Empower local knowledge and leadership:** Large-scale NbS programmes often struggle to effectively engage local and Indigenous communities – despite these groups holding deep knowledge of ecosystems and playing a critical role in sustaining long-term outcomes. Successful, durable NbS requires their leadership from the start.

Conclusion

Strong investment trends in NbS for water security are likely to continue – particularly in countries like China and in Europe, where political commitment, clear policy mandates, and integration into national planning have created a stable environment for investment. Elsewhere, practitioners and experts suggest that future growth will depend heavily on the diversification of financing sources and the ability of NbS initiatives to demonstrate clear value in mitigating water-related risks.

While the overall trajectory of investment in NbS for water is upward, significant structural barriers continue to limit the scale, sustainability, and effectiveness of initiatives. Barriers include:

- Persistent difficulty securing stable, long-term funding to cover both CAPEX and OPEX costs
- Legal and institutional barriers that inhibit investment in NbS
- Lack of stakeholder expertise and capacity to develop and deliver NbS projects
- Difficulty quantifying and communicating the benefits of NbS.

Despite these challenges, the outlook for investment in NbS for water security remains positive. Stakeholders are increasingly aligning efforts across sectors, embedding NbS into broader strategies, and experimenting with blended finance and outcome-based approaches. Public support for water-focused solutions, reinforced by direct experiences with acute water crises, offers a uniquely strong foundation for further investment – if it can be matched by the enabling policies, technical capacity, and coordination needed to realise that potential.

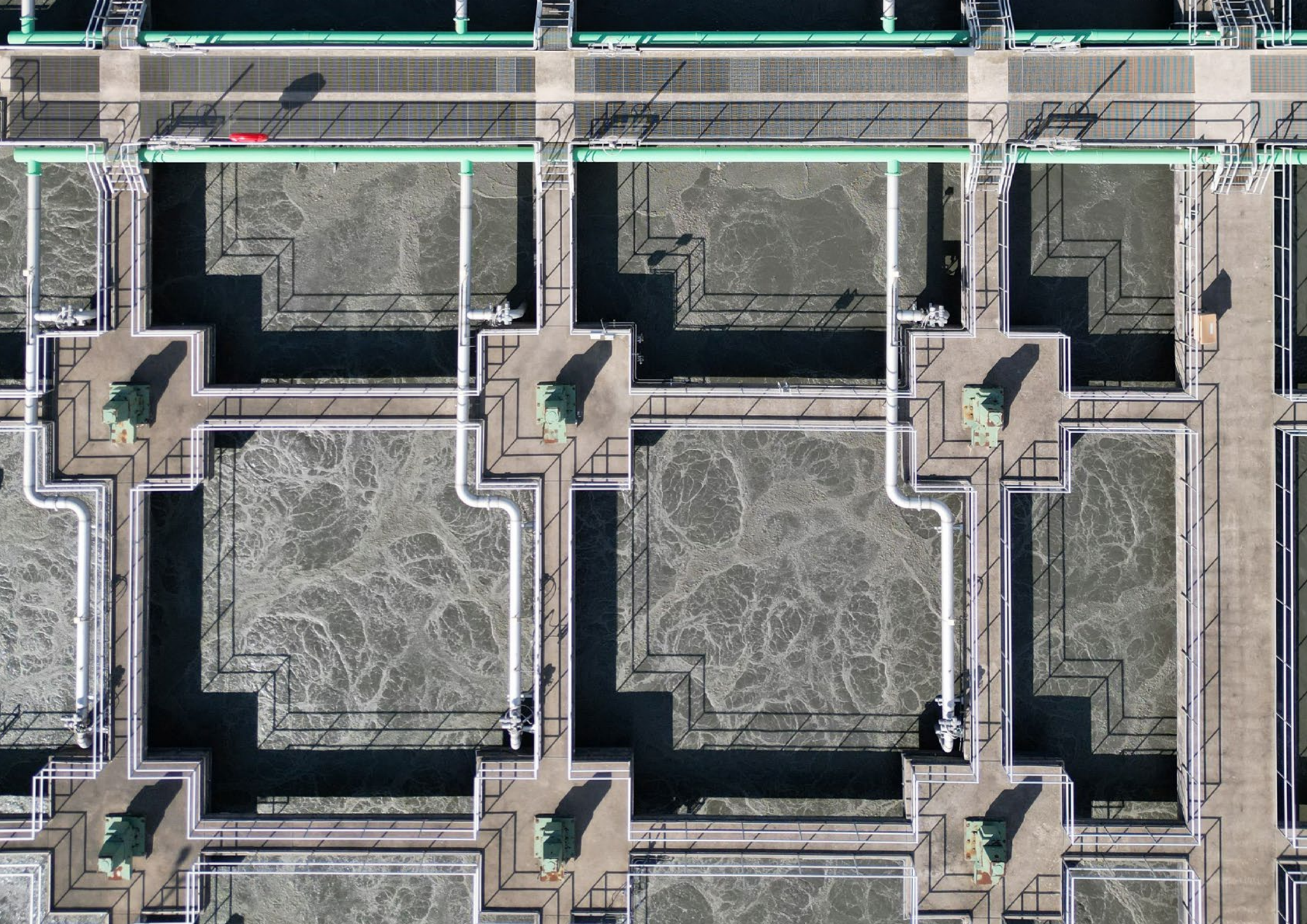
References

Benites, Lucas, and Gena Gammie. (2022). Opening the tap: State of finance for natural infrastructure for water security in Peru, 2021. Forest Trends. https://www.forest-trends.org/wp-content/uploads/2022/02/Opening-the-Tap-State-of-Finance-for-Natural-Infrastructure-for-Water-Security-in-Peru-2021_v2.pdf

IUCN. (2016). Defining nature-based solutions. WCC-2016-Res-069-EN. Gland, Switzerland: International Union for Conservation of Nature. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2016_RES_069_EN.pdf

Smith M., Gammie G., Song J., Atwell B., Shemie D., Bennett M., Cuadros Adriazola J., Joubert I.J., and Tanguy P. (2025): Doubling Down on Nature: State of Investment in Nature-based Solutions for Water Security, 2025. *Report*, Forest Trends & The Nature Conservancy, available from https://www.nature.org/en-us/what-we-do/our-insights/perspectives/investments-in-nature-based-solutions-for-watershed-security/.

SUNASS. 2022. “Enero-Marzo 2022.” Boletin Estadistico: SUNASS En Cifras. SUNASS. https://cdn.www.gob.pe/uploads/document/file/3205397/Sunass-en-cifras-5-1.pdf.pdf?v=1654384733.





Conclusion

The accelerating pressures on global water resources, driven by climate change, population growth, urbanisation, environmental degradation and evolving societal expectations, demand a new level of collaboration across disciplines, sectors and regions. The ability of the IWA Specialist Groups to tap into knowledge and experiences from around the world makes these groups uniquely suited to tackling these global challenges. To be truly successful, the IWA Specialist Groups should be diverse – geographically, generationally, and across disciplines. But they can't stop there. Specialist Groups should actively work together to develop more integrated solutions. The Global Trends Report, by engaging the full array of Specialist Groups in addressing the five themes, has shone a light on areas of commonality and their synergy potential.

Achieving resilient, adaptive, equitable and sustainable water systems will require the active participation of the global water community. IWA's Specialist Groups and Clusters provide a platform for this work, linking expertise across regions and disciplines to move from knowledge to action.

The International Water Association (IWA) Specialist Groups are international communities of water professionals, researchers, scientists, engineers and practitioners who share knowledge and expertise on specific areas of water and wastewater management. They provide a platform for collaboration, professional networking, research, innovation, and the exchange of practical experience.

IWA also brings related Specialist Groups together through Clusters. Clusters focus on broader, cross-cutting challenges that require expertise from several disciplines, such as resource recovery, wastewater-based epidemiological surveillance, biological processes, and nature-based solutions for climate-resilient water and sanitation.

Together, the Specialist Groups and Clusters help connect experts around the world, encourage the development and sharing of new knowledge, and support practical solutions to the growing challenges facing the water sector.

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