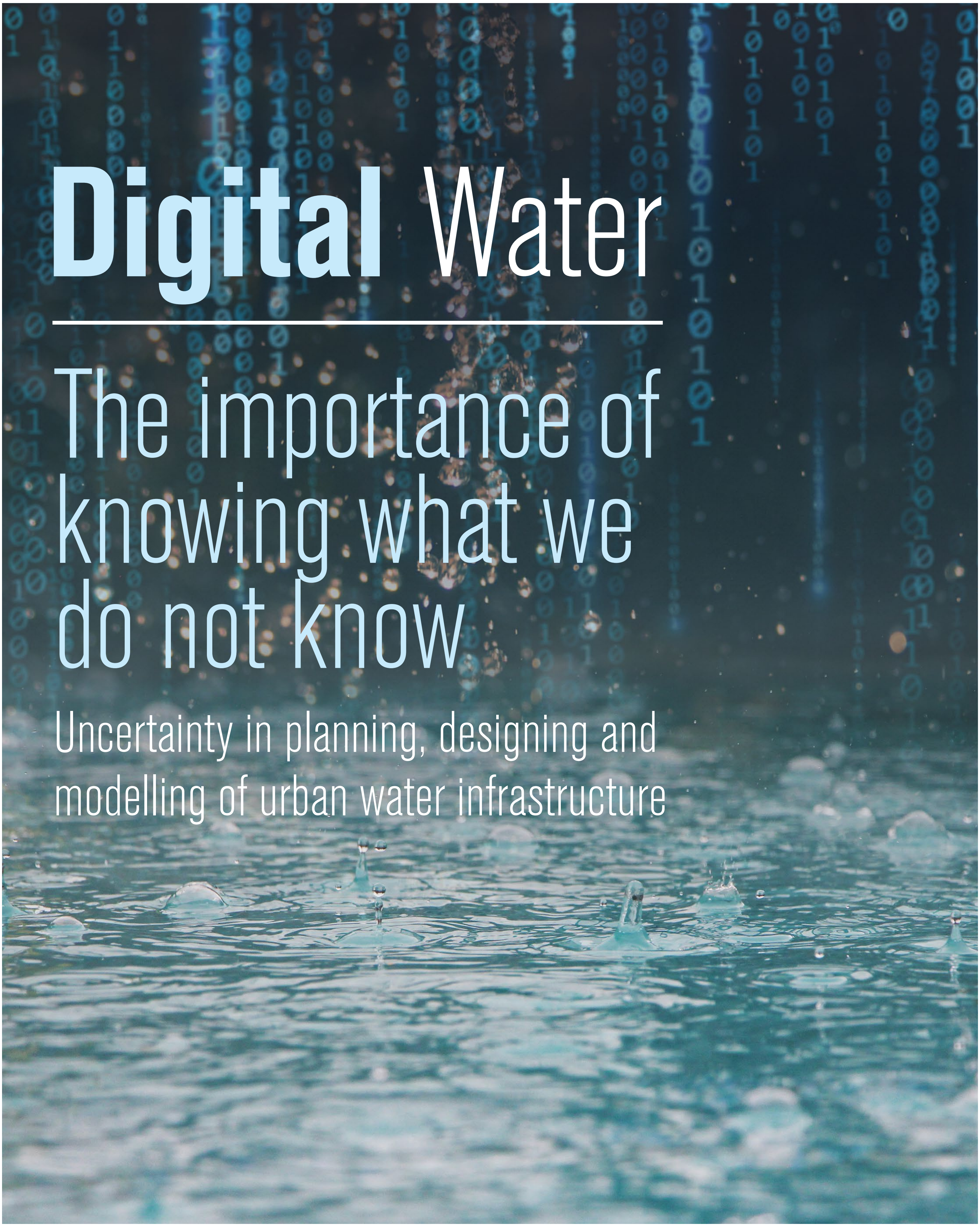
the international water association



Digital Water

The importance of knowing what we do not know

Uncertainty in planning, designing and modelling of urban water infrastructure

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Foreword

Uncertainty governs every aspect of our life: every decision we make can result in unforeseen changes which need to be taken account of and addressed. As the COVID-19 pandemic has reminded us only too well, unforeseen events can reveal cracks in the systems we rely on, from the way we work, to transportation, to the health sector.

The water sector is currently facing a range of challenging dynamic regional and global pressures. This includes climate change, population growth, urbanization, deterioration of urban infrastructure systems, and more. In this context, the future is increasingly uncertain, and change driven by these pressures is occurring at an ever more rapid pace.

It is therefore imperative that our sector recognizes the inherent uncertainties associated with these change pressures and respond with creativity and innovation. New approaches such as real-options analysis acknowledge the value of being able to rapidly expand, down-size or repurpose infrastructure investments. New process technologies are enabling more modular (decentralised) approaches to urban water management. These provide internal degrees of freedom, allowing many different combinations and configurations to be considered, so that flexibility can be optimised over time. In this context, digitalisation of the water sector can act as a "game changer", providing the tools to better capture, integrate and leverage data – in a way that allows us to improve our predictions of future uncertainties and figure out the most optimal strategies for planning and managing our investments in an uncertain world.

The International Water Association (IWA) is inspiring the water sector to adopt a smarter approach to water management. Through the IWA Digital Water Programme, the Association provides the platform that helps water professionals exchange knowledge and experiences on emerging digital technologies and solutions and how these can be integrated across the utility value chain.

To support this journey, the IWA Digital Water white paper series is providing insights into core aspects of the digital world. This latest white paper in the series raises awareness on the many sources of uncertainty in decision-making and describes how digital tools can help water utilities stay in control and improve their decision-making processes. The paper also emphasizes that, while there are large amounts of data being generated by the sector and there is a plethora of analytics tools available, there are still many challenges associated with dealing with different types of uncertainty.

Kalanithy Vairavamoorthy
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Summary

Uncertainty is an often unnoticed aspect of everyday life. The progressing digitalization of the water industry brings more and more data and models into the heart of decision processes. While abundance of data and availability of data analytics tools hold a lot of promise, a wide range of challenges are also associated with different types of uncertainty in data. This whitepaper aims to raise awareness of the many sources of uncertainty in digital decision making and describes how digital water approaches and tools can help us to stay in control and make decisions with (at least some) confidence.

Introduction

Uncertainty is everywhere

Life's full of uncertainty and this is probably one of the things that makes it interesting. We don't know today's special at our favorite restaurant until we go there to find out. We might get stuck in traffic on the way to work if an accident occurs, but we do not know whether or not this will actually happen. And we do not know whether an asteroid will crash down on Earth and wipe out 90% of vertebrate life in 2 years' time. We may choose to be surprised by the restaurant's chef or have a sneak peek at their website (and choose to go elsewhere if we do not like today's special), but cannot know whether a road accident will occur (if we could, we'd take the train instead). And of course, NASA is looking for potential Earth colliding objects, but if they find one heading straight towards our planet, what can we do about it? These are just a few of the myriad of examples that could be chosen to illustrate the uncertainty we are either accepting, by choice or inevitability, or working around in our everyday lives, on different time scales.

Uncertainty in urban water services

Urban water service providers are also dealing with a wide range of uncertainties in their operations and planning. Extreme weather events, which are rare and unpredictable at all but the shortest time scales (but becoming more severe and frequent), pose problems for stormwater systems. In many parts of the world, drinking water is sourced from rain-fed rivers, that may be unpredictable (again on all but the shortest time scales) in terms of their discharge and therefore a river's capacity to supply sufficient water to meet our needs. Drinking water demand, on the other hand, is easier to predict on short time scales (that is to say, it is on the level of a city, but not on the level of an individual person) than in the long term, because behavior changes, new types of water use appliances come to the market, people move, etc.

Why does uncertainty matter?

In a sense, urban water service providers, or at least most of them, are used to long-term thinking. The urban water infrastructure has a life cycle of at least decades but more often longer than a century. This means that thought needs to be given to the requirements not just of today, but also of the decades ahead. And this requires thinking about (uncertain) changes in demand, population size, climate, etc. But there is another reason why uncertainty matters for urban water services. As we are moving towards digital water systems, more and more decisions (either taken by humans or by systems) are based on data and models. For example, the current trend of developing digital twins (twins of the physical infrastructure prototype) requires the understanding of the uncertainty embedded in them as there is no perfect digital replica of complex infrastructure systems. Thus, a more solid basis for informed decision making is introduced, but possibly also a misconception of the completeness and reliability of these data and models.

Data may comprise different types of uncertainties (think of representativeness, measurement errors, communication errors), and models even more so, as long as the urban water service providers do not have accurate and complete descriptions of all their assets. To give an example, if you do not know to what degree the capacity of your cast iron drinking water pipe has decreased due to corrosion and tuberculation, it is impossible to calculate how much water is transferred by this pipe without costly measurements. This means that uncertainty in system state information may result in incomplete understanding of the system's behavior or the wrong decisions being taken (if there even is a clear right or wrong decision). And this is even before considering human behavioral and economic factors, which introduce beliefs, desires, emotions, norms, etc. in addition to rational considerations.

Current developments

The most important of the longer term developments is climate disruption (Pidcock et al. 2019). It is obvious that this will have significant consequences for water management and the human water cycle. Peak water demand is increasing, the availability of water for the production of drinking water, but also for agriculture, is decreasing, the peak discharge of rainwater is increasing, etc. But many uncertainties remain in the magnitude, timing and local effects (in part because they also depend on our future mitigation actions). As is well known, the warming up of Earth's climate will not remain limited to the current value of about 1 degree since the pre-industrial era (IPCC 2018), but will most likely continue to about 2-4 degrees by 2100 (Climate Action Tracker 2019). The temperature rise we have seen so far could, therefore, occur again in just a few decades, i.e., within the lifetime of the infrastructure now being designed and constructed. This brings with it new extremes, although it is difficult to predict their magnitude.

Another relevant development, which is also a source of some uncertainty, is that of population size. Population growth and decline due to births and deaths can be predicted within a reasonable range. However, migration is the most important factor, at least in large parts of Europe and North America. Geopolitics is an unpredictable factor, but climate disruption is possible to an even greater extent. The latter applies both to areas threatened by sea level rise and, even more in the shorter term, to areas that become unlivable due to extreme temperatures and limited availability of water, but also to the areas that will absorb climate refugees. Additional factors related to the population include ongoing urbanization, changing customer expectations, etc.

These developments introduce uncertainties in the demand for and availability of water, and the amounts of stormwater that require dealing with. We need to be aware of these uncertainties when designing and constructing new infrastructure and adapting existing infrastructure.

Different kinds of uncertainty

A distinction can be made between three types of uncertainty of a technical nature, namely unpredictability, structural uncertainty (especially in models) and value uncertainty (especially in data), see Table 1 (IPCC 2007). All three occur in our modelling of water systems and decisions being made. They are associated with the state of objects and the completion of processes, and include stochastic (i.e., randomly occurring) and unknown (i.e., not determined or registered) parameters.

When considering the future, a limited number of scenarios is often used. These describe a potential future event or outcome. Though they have their value, they do not provide a sufficient answer to dealing with uncertainty. It is generally impossible to assign a probability to an individual scenario. Also, a set of scenarios is not intended to be completely comprehensive, nor can it ever be. And it is often difficult to determine which aspects in a scenario are expected to remain the same (stationary) and which are expected to change (non-stationary).

On top of this, there is also ‘deep uncertainty’ (a particular class of wicked problems) where experts do not know – or cannot agree on – the best way to deal with a problem. For example, the deep uncertainty in projections of future sea level rise. This type of uncertainty makes it impossible to rank different aspects of a problem or different scenarios in terms of importance or probability (deepuncertaint.org 2017). The term ‘deep uncertainty’ is used in particular with respect to decision processes.

TABLE 1: SUMMARY OF THE THREE "TECHNICAL" TYPES OF UNCERTAINTY ACCORDING TO THE IPCC (IPCC 2007)

Type	Examples of sources	Typical ways of handling
Unpredictability	Unpredictable expressions of behavior such as the development of political systems	Use of scenarios with a plausible range with a clear indication of these and assumptions, limitations and subjective judgements
	Chaotic processes in complex systems	Judgements Ensembles of model simulations
Structural uncertainty	Inadequate models, frameworks or structures	Clear specification of assumptions and system definitions
	Ambiguous delimitations or definitions	Comparison of models with observations for a wide range of conditions
	Misrepresentation or neglect of relevant processes or relationships	Assessment of maturity of the underlying science
Value uncertainty	Missing, inaccurate or unrepresentative data	Analysis of statistical properties of sets of values (observations, model results, etc.)
		Hierarchical statistical tests
	Wrong resolution in time or space	Comparison models with observations

Reliable and resilient water infrastructure for an uncertain future

There are at least three categories of approaches to deal with this uncertainty using technical methods. To prepare our water infrastructure for the uncertain future, all three will have to be applied.

The first approach is to make people and/or water systems perform well despite changes in our environment and/or conditions. This starts by operating most efficiently at present, i.e., under current conditions. As an example, additional methods for leakage control (ranging from pressure management to model or inspection based leak detection) can be employed. Much work has already been done in this area and many tools are available. Nevertheless, there is still a world to be gained here, given that high leakage rates still occur in many parts of the world including those with water scarcity. Digital water approaches can be a real game changer here, providing tools to accurately detect and localize leaks. Also, the reduction of drinking water demand (by behavioral changes and/or the installation or upgrade of equipment to use less water) (Blokker et al 2017) helps to get the most out of existing infrastructure and postpones investment in new infrastructure. Easy local reuse options such as rainwater harvesting can be encouraged. Then making sure that the system continues to perform well under changing conditions through infrastructural adaptations, for example by increasing the capacity to transfer water between supply areas to mitigate local water scarcity. Doing this successfully requires digital modelling and optimization tools and an adequate digital representation of existing infrastructure and its workings.

Secondly, it is important to increase the resilience of our water supply systems (i.e., the ability to respond flexibly to circumstances that may or may not have changed temporarily) (Nikolopoulos et al 2019). Monitoring, e.g. by sensors and/or remote sensing, helps to understand circumstances and the water system's response to them. A concrete example of the resilience referred to is increasing the possibility of switching between different source types (Stofberg et al 2019) and source areas (geographically). In addition to the availability of these sources, this also requires sufficient capacity for treatment, storage and transport of the water to the right location. This balancing act is of significant complexity, and best supported by digital water technologies for design, optimization and monitoring of resilient water systems. Note that efficiency and resilience are generally competing objectives - an efficient system will have shed the overhead/redundancy required for resilience.

The third approach is to explicitly include uncertainties in model evaluations and predictions. This approach can be combined with the second one in robust/resilient optimization to maximize the capability of a system to deal with adverse circumstances under uncertainty. By quantifying uncertainty as much as possible and expressing it as part of predictions (whether of future water demand or the performance of the system), we at least would know how much trust we can put in these predictions. Moreover, this makes it possible to search for a design or an operating policy that meets the set requirements with a certain probability, which one finds acceptable. For example, one can imagine a water supply system that is capable of supplying 90% of water demand even in the 10% driest summers expected over the coming 40 years. And if we cannot estimate probabilities, we can try to find a solution that performs well under most scenarios.

One-off to continuous process

It is tempting to think that by realizing a design or an operating policy that was optimized for its capacity to deal with adverse conditions, it is enough for the existing uncertainties to be taken care of. However, not all the uncertainties in, for example, how the environment develops can be captured with this approach. This means that in addition to robustness, adaptability to new circumstances is also an important factor in the design (Kwakkel et al 2016). Moreover, this means that designs must be scrutinized from time to time and adapted where necessary.

The Dynamic Adaptive Policy Pathways (DAPP) approach provides a framework for this. This approach considers both measures to be taken to deal with circumstances of the near future and measures that keep options open for later implementation to deal with circumstances of the more distant future. It describes a set of partially consecutive policy actions and their interactions, and monitors changes that lead to the failure of immediate measures, requiring the new measures to be put in place. For example, putting buckets under a leaky roof instead of replacing the tiles is a cheap solution in the short run, but this may result in the beams of your roof rotting away, which eliminates the option of just replacing the tiles in the future (since the whole roof will need to be replaced then). But until you manage to replace the tiles, the buckets may be an acceptable temporary solution.

The digital water paradigm provides the tools for dealing with uncertainty

Hydroinformatics, operating at the interface of ICT and water applications, offers a toolbox to deal with the various aspects of uncertainty. Table 2 gives an overview of the types of tools available to support strategic/policy choices and the design of subsystems of the drinking water supply. The successful application of these tools hinges on the availability of adequate digital representations of systems and infrastructure and their behavior, i.e., models and data. An illustrative selection of example applications is included for demonstration purposes.

TABLE 2: TYPES OF TOOLS FOR DEALING WITH UNCERTAINTY WHEN CONSIDERING OR PREDICTING DRINKING WATER SUPPLY

	description	example applications
(peak) Demand forecast	Longer-term water demand forecasting, based on (a) assumed future behavior and technology or (b) relationships in recent water demand variations	Blokker et al 2017, De Souza Groppo et al 2019
Design and optimization tools	Design, operation and dimensioning of infrastructure, numerical optimization based on objectives and preconditions	Morley and Savic, 2020, Maiolo et al 2017, Jiang et al 2020
Scenario and optioneering tools (which calculate the consequences of scenario choices) and serious games	Tools for calculating (e.g., capacity) the impacts of different scenarios and options for building systems and policies related to these systems	Nikolopoulos et al 2019, Water Sensitive Cities Scenario Tool
Serious games	Tools for evaluating and visualizing the effects of policy decisions in an abstracted but meaningful way in order to facilitate discussions and decision making processes in a multi-stakeholder setting	Savic et al 2016, sim4nexus.eu

Reducing uncertainty

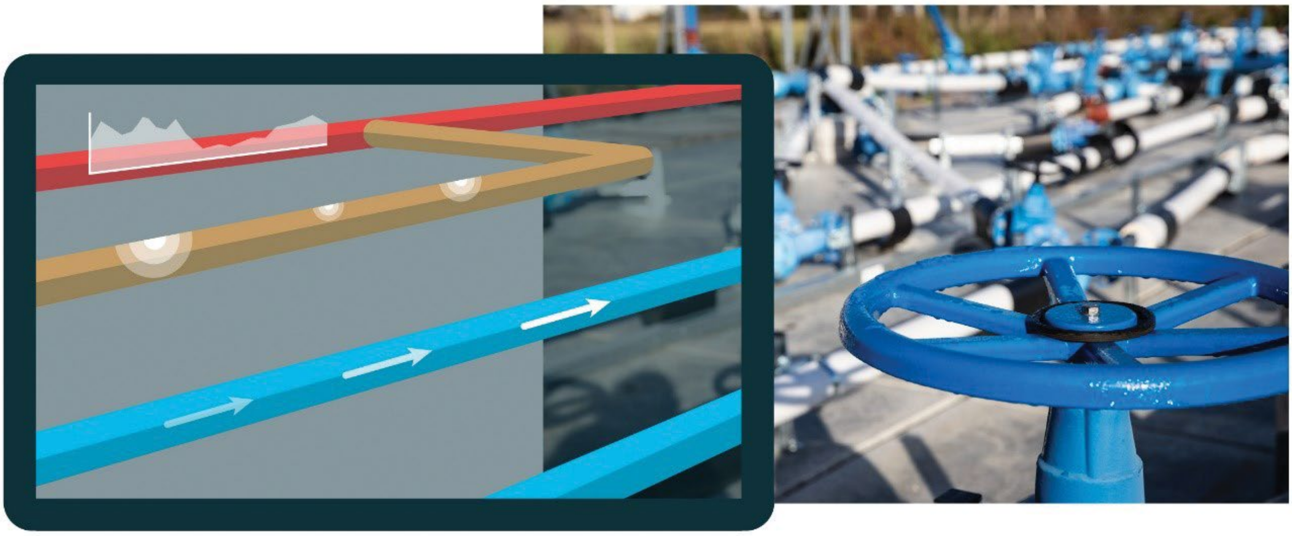
Structural uncertainty (unsatisfactory models, frameworks or structures in various ways, for example the detailed layout of a water network) in physical models can, in principle, be reduced gradually by continuous improvements in model representations. These improvements may arise from insights gained from the practical application of models. This is, however, not true for models that include social and behavioral elements, because of potential feedback between the model and behavior.

But it is the value uncertainty in particular that provides the best opportunities for improvement. The knowledge of our systems and processes increases rapidly with the introduction of sensors and inspection techniques, which provide us with more information about the processes and also about the infrastructure itself. And it seems that we are only at the beginning of this development. Also, more and more environmental data is becoming freely available, which allows us to reduce uncertainty by replacing generic estimates or extrapolations from low resolution data previously used in models and decision support systems.

Communication of uncertainty

We have become used to seeing and understanding one of the simplest forms of visualization of uncertainties in ensemble and bandwidth plots. These are commonly used in communicating weather forecasts or predictions of global warming and sea level rise including the associated uncertainties. They work quite well for single parameters, but for more elaborate systems, this method of visualization quickly becomes too complex and a more sophisticated approach is required. Depending on whether the complete system is considered, or one is looking at a minute detail, different levels of aggregation on the uncertainty bounds can be applied (e.g., aggregated variances to full histograms). This also depends on who is looking at the data. Researchers doing data exploration need more control on the visualization of uncertainties than end users of data presentation. Augmented Reality (AR) applications may help to reduce uncertainty with respect to, e.g., infrastructure layout and geometry - an overlay of the digital (holographic) representation of the infrastructure on top of the real thing makes deviations very easy to recognize (Figure 1). This AR technology is particularly useful for field personnel to see the augmented view of buried water infrastructure and locate possible solutions, e.g., detect valves to be closed to isolate a leak. On the other hand, Virtual Reality (VR) may be a very useful tool to explore in a safe environment various future scenarios, representative of the state of uncertainty and in optioneering. Future use of VR in the water industry might be to improve visualization for serious gaming tools.

FIGURE 1: AUGMENTED REALITY APPLICATIONS CAN PROJECT ADDITIONAL INFORMATION ON PHYSICAL ASSETS



Are we ready for the uncertain future with digital water?

Technically, the representation and propagation of uncertainty need to become standard steps in building and using models to design and operate urban water systems. This applies to models of entire systems, sub-systems (purification, distribution network, stormwater network), but also, for example, to numerical optimizations that make use of these models. Work to include uncertainty in these models has already been done in academic circles, but this has not yet seeped through to operationally applied software in practice.

Applied research institutes and software providers aimed at the water sector still need to develop this operationally applicable software. Also, with regard to methodologies for dealing with uncertainty and decision-making under (deep) uncertainty, a lot of work has already been done in the academic world and in other application fields, which can be adapted for and applied in decisions about our urban water systems.

However, the technical aspects are only one side of the story. Communicating and fine-tuning the results, and taking decisions based on them, is still a different story. The complexity and comprehensiveness of probabilistic results require a new way of visualization and interaction with the results. This has to be done in such a way that all stakeholders can be involved and easily understand the essence of the consequences of different alternatives for their own area of interest and that of the other stakeholders. The (further) development of serious games that allow stakeholders to visualize and discuss the effects of their own and each other's policy decisions (e.g. Savic et al 2016, sim4nexus.eu 2020) can offer a solution in this respect.

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