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Hydroinformatics and Smart Water Management - Current State and Opportunities for the BTO Utilities

KWR

Bridging Science to Practice

Hydroinformatics and Smart Water Management - Current State and Opportunities for the BTO Utilities

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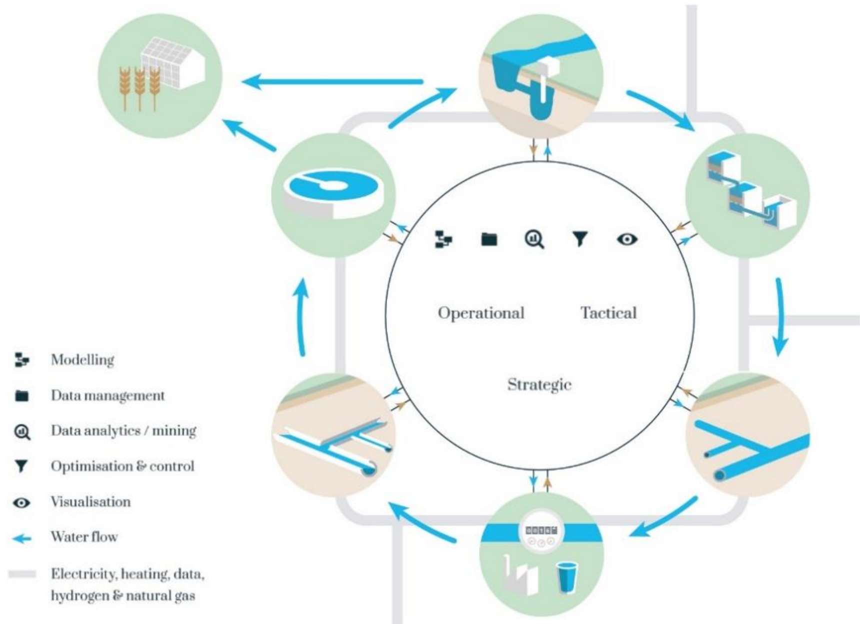
BTO Managementsamenvatting

Nieuwe visie biedt kader voor invulling verdere ontwikkeling hydroinformatica en smart water management

Auteurs Dr. J. (Joep) van den Broeke, Dr. T. (Tessa) Pronk, Dr. D. (Dirk) Vries, Dr. P. (Peter) van Thienen

Met de voortschrijdende digitalisering en connectiviteit van de samenleving op alle niveaus wordt de verwerking van steeds meer gegevens en de valorisatie van informatie steeds belangrijker. Hydroinformatica en smart water management kunnen bijdragen aan het versterken van de toekomstbestendigheid van de watersector. Er is een visie ontwikkeld op de digitale watersector van de toekomst, bouwend op een analyse van de huidige stand van zaken en van technologische trends. Deze visie identificeert kansen en risico's en is bedoeld als kader voor verder denken en discussiëren en om de agenda voor onderzoek, ontwikkeling en toepassing te helpen bepalen.



Schematische weergave van de ontwikkelde visie op de rol van hydroinformatica (HI) en smart water management (SWM) in de watersector, die meerdere dimensies omvat: de zeven domeinen binnen de watersector (van bron tot afvalwaterbehandeling en watergebruik voor voedsel, energie en industrie), vijf onderdelen van hydroinformatica en smart water management (modelleren, data management, data-analyse en –mining, optimalisatie en beheer en visualisatie) en drie niveaus waarop zij worden ingezet (operationeel, tactisch en strategisch).

Belang: omgaan met toekomstige uitdagingen

Op alle niveaus van de samenleving neemt digitalisering en connectiviteit toe en dat brengt met zich mee dat het verwerken van gegevens en de valorisatie van informatie ook steeds belangrijker wordt. De verwachting is dat in de watersector net als in andere industriële sectoren het gebruik van gegevens en verdere digitalisering zullen helpen om de sector toekomstbestendig te maken en het hoofd te bieden aan uitdagingen als klimaatverandering, bevolkingsgroei, verstedelijking en migratie, nieuwe opkomende stoffen in water, en verouderende infrastructuur. Ook in de watersector zijn de verwerking van gegevens en de valorisatie van geëxtraheerde informatie, digitale optimalisatie en besturing van systemen, modelgebaseerde besluitvorming en het genereren van scenario's inmiddels onontbeerlijk geworden. De informatiekunde, data science en digitale technologie die daarvoor nodig zijn, maken pas relatief kort onderdeel uit van de bedrijfsvoering in de watersector. Samen vormen zij de jonge werkvelden hydroinformatica (HI) en smart water management (SWM): bijzonder interdisciplinaire werkgebieden die kennis en methoden integreren uit elk watergerelateerd domein waar gegevens worden verzameld en verwerkt. De afhankelijkheid van Nederlandse en Vlaamse drinkwaterbedrijven van HI en SWM neemt snel toe, terwijl deze werkvelden tegelijkertijd nog in ontwikkeling zijn. Om die ontwikkeling goed vorm te geven, is een visie nodig als kader voor gezamenlijk verder denken en discussiëren en om de agenda voor onderzoek, ontwikkeling en toepassing te helpen bepalen.

Aanpak: stand van zaken watersector, technologie en trends verzameld als basis voor visie op 2030
Voor het ontwikkelen van deze visie hebben onderzoekers kennis over HI en SWM gecombineerd met een overzicht van technologische trends en van kwesties en vraagstukken die spelen in de watersector. Zij hebben de huidige stand van zaken op het gebied van HI en SWM geschetst bij KWR, in Nederland in het algemeen, en wereldwijd. Op die basis hebben zij een visie geformuleerd op de rol van HI en SWM in de watersector, in het bijzonder de Nederlandse en Vlaamse watersector, op de middellange termijn (2030).

Resultaat: kansen voor de waterbedrijven
De ontwikkelde visie identificeert de kansen die de watersector met HI en SWM kan benutten en de risico's die zij ermee kan aanpakken. De hieronder beschreven visie is niet in steen gebeiteld, maar biedt een waarschijnlijk beeld van de toekomstige ontwikkelingen. Op dit moment is informatie over de toestand van (begraven) assets en de kwaliteit van het water slechts op een klein aantal specifieke plaatsen en tijdstippen beschikbaar. Een ideale omgeving stelt alle informatie beschikbaar die nodig is om met kennis van zaken beslissingen te nemen over actuele en toekomstige kwesties, en voorspellingen te doen over de toekomstige staat en werking van het systeem. In een toekomst met een geavanceerde informatievoorziening kunnen kwalitatief betere beslissingen worden genomen op operationeel, tactisch, en strategisch niveau, omdat HI en SWM veel van de onbekende parameters zullen elimineren die van invloed kunnen zijn op de uitkomst van een besluit. Dit zal resulteren in betere conceptkeuzes, betere systeemontwerpen en betere bedrijfsvoering, waarbij beter in dit verband betekent: effectiever, efficiënter, goedkoper of betrouwbaarder. De spelers in de waterkringloop zullen daarmee beter zijn toegerust om toekomstige uitdagingen het hoofd te bieden.

Toepassing: het vaststellen van de agenda voor onderzoek, ontwikkeling en toepassing
De visie kan dienen als denkkader en als basis voor discussie om te helpen een agenda vast te stellen voor HI- en SWM-georiënteerd onderzoek en ontwikkeling. De uiteindelijke maatstaf voor het succes van HI en SWM – namelijk ons vermogen om wetenschappelijke en informatietheoretische ontwikkelingen in de praktijk om te zetten ten behoeve van de watersector en de samenleving als geheel – wordt bepaald door de sterkte van vier pijlers:

1. een veilige, geïntegreerde data-infrastructuur gekoppeld aan sensoren en actuatoren, een oplossing voor gegevensbeheer, en beschikbaarheid van (software)tools of embedded software, inclusief langetermijnondersteuning;
2. inzet van data scientists en hydroinformatici en ondersteuning van kennisoverdracht binnen en tussen waterbedrijven en –instellingen;
3. steun voor onderzoek en ontwikkeling van HI, vooral daar waar IT-ontwikkelingen nog niet zijn omgezet in oplossingen voor de watersector;
4. de overtuiging dat slimme watersystemen de uitdagingen van vandaag en morgen aankunnen.

Rapport
Dit onderzoek is beschreven in het rapport *Hydroinformatics and Smart Water Management - Current State and Opportunities for the BTO Utilities* (BTO 2019.045).

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1 Introduction

1.1 The water sector in a rapidly digitising world

With the advancing digitisation and interconnectedness of society at all levels, the handling of data and the valorisation of information extracted is an increasingly important issue. Developments that leverage new technology offer the water sector opportunities to do things differently. This comes at the right time, since the water sector is now being confronted with a wide range of challenges, such as climate change, population growth, urbanisation and migration, chemicals of emerging concern, and ageing infrastructure, for which solutions need to be found. As in other industry sectors, harnessing data and the versatile options of further digitisation are expected to help make the water sector future-proof. The handling of data and the valorisation of information extracted, digital optimisation and control of systems, model-based decision-making and scenario generation have become indispensable.

Information science, data science and digital technology are relatively recent additions in the workings of the water sector. Reliance on such technology is, however, rapidly increasing and stakeholders at all levels are finding their way in this new digital reality. All these aspects are encompassed by the fields of hydroinformatics and smart water management, which are concerned with the development and application of information technology in and for the water sector. The two fields are truly interdisciplinary because they integrate knowledge and methods from any domain where data are collected and processed (Figures 1.1 and 1.2).

This report aims to provide a vision on the digital water sector of the future. This vision is based on an analysis of the current state-of-play and of technology trends. This vision will be used to identify opportunities to be exploited and risks to be addressed in several contexts, including the BTO programme. This will be done in a workshop with the BTO participants, to be organized in September 2019.

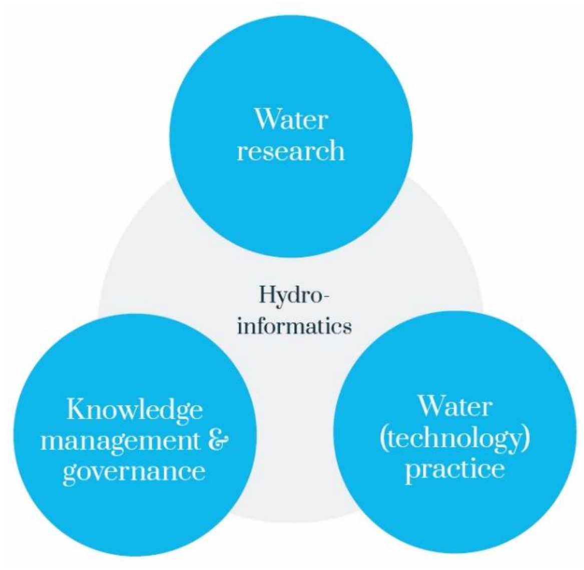

Figure 1.1: The role of hydroinformatics as an interdisciplinary link between water research, knowledge management & governance, and water practice.

1.2 Definitions

For the purpose of the discussions in this report as well as supporting the vision and mission statements developed, the following definitions will be used:

Hydroinformatics
Hydroinformatics (HI) is the scientific field in which information technology, in its broadest sense, is developed for and applied to water-related practices, combining technological, sociological and environmental perspectives.

Specifically, hydroinformatics is essentially about:
- the interdisciplinary scientific study of the complex water cycle system and its challenges;
- leveraging ICT advances to deliver more sustainable and resilient water management;
- having the required data (both volume and quality);
- having the necessary digital tools available;
- using data and tools to develop an understanding of our environment;
- engaging stakeholders;
- helping make decisions that improve our society.

Smart Water Management
Smart Water Management (SWM) is the application of hardware, software and human capabilities to improve the design, situational awareness, control and performance of water systems or subsystems.

Smart Water Management integrates and harnesses data from the water system and the associated environment, to increase the system's efficiency and effectiveness and reduce risks.

The water sector
KWR has traditionally focused on all aspects of drinking water supply, from source to tap, including hydrology and water safety. In recent years it has expanded its scope to encompass a more holistic view, which includes wastewater collection and treatment, resource recovery and water reuse, energy storage and management, system resilience as well as governance aspects. In this report, the term water sector refers to this broader context, i.e. entities dealing with any aspect of the complete human 'water cycle'. In addition, the definition expands to the necessary integration of this water cycle with other sectors where water plays a major role, and ambitions such as the 'circular economy' or 'smart cities'.

Figure 1.2 presents an ontology that further clarifies the hydroinformatics and smart water management concepts, and represents their interdependent characteristics and their connection with the water cycle and the world at large.

Hydroinformatics vs Smart Water Management
Although hydroinformatics and smart water management both deal with the use of information technology to address water-related issues, hydroinformatics has a much larger scope.

Hydroinformatics focuses on developing tools to support decision-making at all levels, from operations to governance and policy, through (data) automation, optimisation and control. Examples of hydroinformatics applications include studies, such as river basin analyses, datamining for identification of unknown substances and modelling of water quality and quantity, e.g. in the aquatic environment, water production, supply and reuse processes or in water-related health studies.

Smart water management, in turn, is more practice-oriented than hydroinformatics; it focuses on making the most of water resources by leveraging data for action, while drawing on the field of hydroinformatics for its solutions. Smart water management applications aim to increase efficiency and effectiveness of water systems, i.e. doing more with less (money, time, and/or resources). Examples of applications include process control (real-time, near real-time), resource planning based on measurement data (medium term), and system design (long-term goals). In this context, the smartness in a smart water system can be classified as hydroinformatics, but the application of hydroinformatics does not necessarily classify as smart water.

The different focuses of the two disciplines are also reflected in the communities that associate with them: hydroinformatics is the term used mostly in science and academia, while smart water is the term that is most often used in business.

Although we have seen that hydroinformatics and smart water management are separate, albeit closely linked, working areas, the purpose of this report is best served by treating them as a single discipline. In the chapters that follow, therefore, we will refer exclusively to ‘hydroinformatics’, with the exception of those instances where there is an explicit added value in referring to smart water management as a stand-alone discipline.

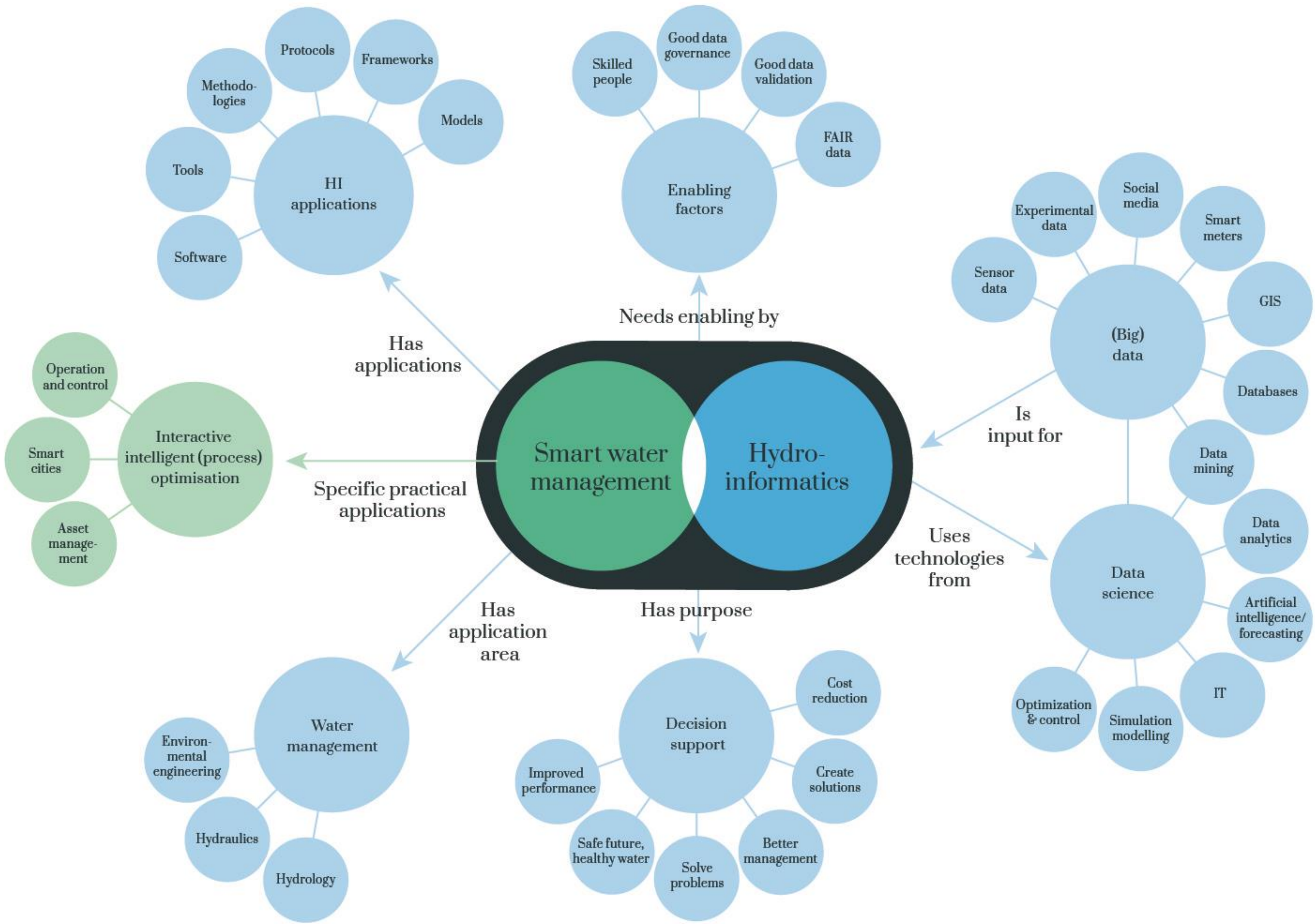

Figure 1.2: Hydroinformatics and smart water management ontology.

1.3 Scope of this report

The coordinating body (CO) of the joint research programme of the Dutch and one Flemish water utilities (BTO) has asked KWR to provide a sketch of the data- and model-driven drinking water utility of the future. The intention of this report is to provide a suitable background for such a sketch (or *vision*) by describing current developments and relevant actors in the fields of HI and SWM, and also by describing relevant activities at KWR. Building on these, our vision of the data- and model-driven drinking water utility of the future is presented. It is intended as a discussion document and as an anchor for initiating and/or continuing the required developments both within and outside the framework of the BTO.

1.4 Approach

The approach taken involved:

1. Describing the current situation regarding hydroinformatics and smart water management at KWR, in the Netherlands generally and worldwide. This not only gives insight into the current place of KWR in the world of hydroinformatics, it also provides insight into the experience and capabilities available within the organisation.
2. Formulating a vision of the role of hydroinformatics and smart water management in the water sector[1], and for the Dutch situation in particular, over the medium-term (10-year horizon). The overviews of the present situation, experience and trends were produced from readily available knowledge, supplemented by desktop research and interviews with, and written feedback from, KWR colleagues involved in hydroinformatics. The water sector vision was created on the basis of an interpretation and extrapolation of technological and societal trends and describes both the technical aspects and the benefits and opportunities that their application brings

1.5 How to read this report

Chapter 2 describes the current state of hydroinformatics in the national and international water sectors, including relevant trends in technology and society, and at KWR. Our vision for the water sector is presented in Chapter 3.. Finally, Chapter 4 presents some concluding remarks.

[1] In this context, the vision consists of a description of how the water system could operate, with the assumption that the effects of hydroinformatics and smart water management will be beneficial

2 The state of hydroinformatics and smart water and relevant technological and societal trends

Various digital technological and societal trends are changing the environment in which the water sector operates. In this chapter we outline these trends, provide the current state of affairs regarding hydroinformatics (HI) and smart water management (SWM) and sketch the progress of adopting digital concepts by actors in the Dutch water sector and the perspective of the EU. A selection of projects in which BTO members and KWR participate is used to illustrate developments.. All the above elements form a basis of our vision on how HI and SWM will change the water sector in the upcoming 10 years, which is the subject of the next chapter.

2.1 Enabling technologies and trends from society

This section discusses a selection of current technological developments that may contribute to HI and SWM helping to improve efficiency, resilience and sustainability.

2.1.1 Technologies

1 **The internet of things** (IoT), and more generally, sensing techniques, actuators and modern control, enable the development of integral solutions that optimise management of energy, food and water cycles, especially in the context of urbanisation, climate change and related water scarcity or extreme weather events. These trends are already seeping through to the water sector. The IoT is a network of devices, such as vehicles or home appliances, that are interconnected and contain electronics, sensors and actuators, such that the devices can interact and exchange data. These interconnected sensor networks provide the basis for real-time insight into water quality, water quantity (including water safety), and customer awareness of water and energy consumption. In the future, automation and control of services in water supply and management will become a reality, when these networks are driven by artificial intelligence or other type of water infrastructure models. Note that these developments in particular introduce an additional element of exposure of water system components to potentially malevolent agents through the internet, and therefore require appropriate attention to cybersecurity, as described in Section 2.1.2

2 **Cloud computing**, which encompasses the availability of high capacity networks, servers and storage infrastructure as well as the adoption of virtualization, service-oriented platforms and 'computing on demand' services, is nowadays a proven concept. Cloud computing provides large computational capacity and storage, without the IT burden and obstacles that occur when computing is performed on an in-house network. For the water (and energy) sector, cloud computing and online computational tools hold the promise that data science applications, dashboards or decision support tools can be developed and deployed quickly, without having to expand or modify existing in-house IT infrastructure and services. As in the case of IoT, this approach introduces an additional exposure of water system data to potentially malevolent agents through the internet, requiring attention to cybersecurity.

3 **Augmented/virtual/mixed reality** will change the way we work, and possibly the way we live. With virtual reality, a computer simulates an environment and provides auditory and visual feedback, and sometimes other types of sensory feedback, to create an immersive environment that feels real. With augmented reality (AR),

computer generated components or objects are overlaid ('augmented') on the real image that we see or perceive. In mixed reality (MR), a scan of a real environment becomes a 3D object, to which extra information in 3D can be added. This is more interactive than AR or VR. Virtual and augmented reality have been explored for many applications, from gaming and entertainment to medicine, education and (marketing) business. Currently, AR technology is being tested in Spain[2,] (with the aid of the consulting firm Acciona) and Japan[3] (serviced by Fujitsu, an IT company) at water treatment sites, for the purpose of quality control, incident reporting, diagnosis and maintenance. It is only a matter of time before these developments are translated to other parts of the water sector and combined with predictive analytics for optimal maintenance, for instance.

4 **Digital twins** are digital replicas of living or (non-living) physical entities, like processes, people, places, systems and devices that can be used for various purposes. With digital twin technology one can simulate these entities and update and change the represented entity as their physical counterparts change. In various industrial sectors, digital twins are being used to optimise the operation and maintenance of physical assets, systems and manufacturing processes, using a combination of artificial intelligence, machine learning, IoT or sensors and software analytics. For instance, Northumbrian Water and Newcastle University[4] are exploring the potential of using digital twin technology to help predict the impact of a burst pipe or heavy rainfall.

5 Encapsulating **artificial intelligence (AI)** and deployment of autonomous systems. The development and implementation of AI techniques, including machine learning and *deep learning*, have taken a big leap in the last decades. Image recognition (e.g., face detection and identification) and speech recognition are perhaps the most widely known implementations of deep learning. More generally, AI is used successfully for recognizing patterns in the marketing and financial sectors. In the water sector, AI can be adopted for example for (semi) autonomous systems, anomaly detection, predictive maintenance, monitoring and optimal (feedforward) control. In addition, drinking water utilities and water boards have organised data challenges in recent years. AI promises to provide support on the operational level, for example, in the smart control of water collection and water treatment processes[5,6], and on the tactical and strategic level with, for example, predictive maintenance and decision support. It should be noted that streamlined data management, close collaboration between data scientists and water experts, sensoring (e.g., in water or sewage networks), and support from clients are the key to successful implementation of AI techniques. In practice, one of these elements is often lacking.

6 **(Semi) autonomous systems** to automate tasks are becoming a reality in the water sector. For instance, operational and maintenance tasks in water management are being conducted by the deployment of unmanned aerial vehicles (also known as drones). In the Netherlands, autonomous inspection robots for sewer and drinking water distribution systems are being developed in research collaborations[7,8] . In the future, the integration of AI with robotics will enable (semi) autonomous control of water treatment, distribution and water management processes on the operational level, and predictive asset management on the tactical and strategic levels.

7 **Quantum computing** is an alternative approach to conventional computers that employs the quantum mechanical principle of superposition to perform an evaluation of great numbers of candidate solutions simultaneously to arrive at a single desired solution. Quantum computing is believed to have potential for the

[2] https://www.imnovation-hub.com/water/augmented-reality-address-challenges-water-cycle/

[3] From: https://blog.uk.fujitsu.com/cloud/how-wearable-tech-is-about-to-transform-utilities/

[4] From: https://wwtonline.co.uk/news/northumbrian-explores-twinning-approach-to-incident-response

[5] Stowa report 2005-047: Application of neural networks and fuzzy logic - Artificial Intelligence in water management. ISBN90.5773.279.3

[6] For instance, the German company Aquatune GmBh is involved in control of wastewater treatment plants using machine learning techniques.

[7] AIR project, see https://www.tkiwatertechnologie.nl/project/ontwikkeling-autonome-inspectie- robots-airs-voor-het-drinkwaterdistributienet/

[8] Stowa report 2005-047: Application of neural networks and fuzzy logic - Artificial Intelligence in water management. ISBN90.5773.279.3

water sector in several applications requiring ultrafast computation (optimisation, artificial intelligence, cryptography).

8 **GPGPU** is the use of Graphics Processing Units as General Purpose coprocessors for accelerating (particularly) matrix operations in which significant performance gains can be realised through Massively Parallel Processing (MPP). This technique is particularly efficient when applying relatively simple operations to many data points simultaneously (c.f. matrix transformation of coordinate systems), and is useful for applications such as cellular automata or those that rely on large-scale matrix computation, Computational Fluid Dynamics and Finite Element Modelling. Similar performance improvements can be realised for a wider range of applications (optimisation, deep learning) through the use of coprocessors such as Intel's Xeon Phi.

9 With **block chain technology**, cryptography is combined with the ability to store and register transactions in a decentralized manner (this concept is also referred to as 'digital ledger technology'). By definition, block chain is a ledger of all transactions that have been executed and could be seen as a write-only platform, wherein transactions once executed cannot be modified later. For water sector applications, this is a way of preventing attackers from tampering with sensor data. More generally speaking, block chain can be applied to many data transactions in the water sector, including joint databases from various partners. Apart from its popular use for cryptocurrencies like Bitcoin, start-ups find use for block chain technology in identity verification, contracts, the energy market[9], and secure distributed data in IoT systems[10]. A major drawback of block chain technology is the need for computational resources, and thus energy, to perform the verification computations. This may reflect negatively on corporate image in the context of sustainability. As in the case of the energy market, block chain technology could find its way into the water sector by securing IoT networks. Alternatively, cryptographic solutions could also be safely managed in the cloud[11] without having to rely on block chains. The latter is more suited for centrally securing data networks of water utilities.

10 **Remote sensing** is a collective name for techniques to gather information on objects by equipment that does not have direct contact with the objects. The equipment can be a satellite, air balloon, drone, ship or another robot. Remote sensing allows for the investigation of areas that are hard to reach. Remote sensing can be active, when it sends out signals that interact with the object and are subsequently measured (e.g., electromagnetic pulses) or passive, when for example it simply observes the system by taking photographs. The quality of remote sensing information is among other things dependent on resolution (time, space, spectral or radiometric composition) and post-processing options, such as correcting for cloudiness in satellite images.

2.1.2 Trends in society

There are many organisational prerequisites for the adoption and implementation of HI and SWM applications. The most important are described here:

1 24/7 functioning of vital water services in drinking water supply and water management is at risk when (cyber) **security** is not prioritised; this is often overlooked, especially for IoT systems. Cyber-attacks are a growing threat to energy grids, water infrastructure, financial markets, transportation infrastructure and elections. Examples of

[9] For instance, the German company Aquatune GmBh is involved in control of wastewater treatment plants using machine learning techniques.

[10] www.designnews.com/electronics-test/filament-making-blockchain-iiot-easy-usb/80716323059036

[11] As an illuminating example, Secrethub, the platform of the Dutch start-up company KeyLocker B.V., provides (key management) software as a service. The company has run a pilot at Hoogheemraadschap Delfland (www.vpdelta.nl/nl/nieuws/cryptochip-startup-keylocker-beveiligt-waterwerken-hoogheemraadschap-delfland).

such attacks include: (i) the use of DDoS[12] to disrupt internet servers by flooding the target machine with requests in an attempt to overload the target system; (ii) phishing and spoofing[13] attacks to gain illegitimate advantage or access; (iii) the dissemination of incorrect information ('fake news') by semantic attacks; and (iv) the spreading of 'malware' (viruses, worms, Trojan horses ransomware). (Cyber)security is directly related to geopolitical developments, including issues such as trade wars and the future of the EU.

2 Data transfer and sharing across sectors and within water utilities is enabled by findability, accessibility, interoperability and reusability (FAIR[14]). **FAIR data** principles are being rapidly adopted in science. Combined with the development towards *open science and open government data*, FAIR will enable data users to find, access and reuse data. This will put more emphasis on required skills in finding and preparing data for reuse, as well as knowledge of ethical aspects of data reuse. The principles and developments require that, at the other end, data owners and developers (hydroinformaticians) think about *how* data are shared, for example, by using (computer readable) standards for documentation,metadata and programming interfaces, according to the principle of 'as open as possible, as closed as necessary'. FAIR data sharing has the advantage that transparency is increased and provides opportunities for the water sector in engaging citizens, improving efficiency, knowledge, interoperability and collaboration, and accelerating innovative IT solutions. A special role in data transfer is foreseen for storing and sharing data as 'linked data'. As relations between data points are explicit in linked data, the data collection is virtually unending, as new data can be linked. All data are computer interpretable. In the DSO (Digital Systems Environment and Planning Act)[15], a transition is planned to move towards sharing data via linked (open) data in 2024. The water sector will have to take this into account.

3 Developments in society, due to the **use and abuse of social media**, like Facebook, Instagram, Twitter, YouTube and the like, can have serious consequences for organisations and regional authorities that operate in the public space. But messages on social media also provide the opportunity to understand and engage with customers and to assimilate these data; for example, for better leakage location in the water distribution network, or information about groundwater levels in the water system, in the case of extreme weather events or malfunctioning water (safety) infrastructure. As an illustrative example, the engineering and consulting firm Royal Haskoning DHV has developed a platform where Twitter messages are gathered, searched for water-related content, and geographically visualised together with other customer data (like telephone calls) and operational data. On the 'threat' side of matters, real and 'fake news' can instantly dominate the current consensus regarding current (governance) practices in water management and water supply.

4 **Strengthening governance**, that is, a hybrid approach where humans are still in control but (operational/tactical/strategic) processes are supported by HI and smart water systems.

5 The trend towards **escapism** is important for hydroinformatics, as society and end-users may become tired, sceptical or distrustful of automated systems or complex applications, and long for more natural/simple/human ones. This may impede progress or prevent the adoption of hydroinformatics applications or technologies. Also, water utilities that use social media in their interaction may lose contacts.

6 The trend towards **gamified motivation**. The essence of this trend is that the (social) behaviour of individuals or groups can be influenced by the desire to earn points, badges, or other marks of achievement for 'correct' behaviour. In online discussion fora, for instance, participants with good input earn points, which motivates

[12] Distributed Denial of Service

[13] With spoofing, a person or program successfully masquerades as another by falsifying data. Phishing is the attempt to obtain sensitive information through the disguise of a trustworthy entity in electronic communication.

[14] https://www.go-fair.org/fair-principles/

[15] https://aandeslagmetdeomgevingswet.nl/digitaal-stelsel (in Dutch)

them to provide more good input. Gamification could be deployed for water demand management, by motivating customers to save water[16]. A point of concern is privacy, for instance regarding the storage and deployment of the data on individuals. Care should be taken to follow the European general data protection regulations and have ethics in full view.

7 Related to this is **Serious Gaming**, which is a way to inform on, create insight into, and teach serious topics in an entertaining way, in the form of a game. The game can take many shapes. Games often have a technological aspect, such as interfacing and controlling with touchscreens, motion control, virtual maps, interactive interfaces, interactive simulations and biofeedback. Examples of applications of games include raising awareness of the socio-techno-economic issues related to managing complex water systems[17], or testing the potential cross-sectoral implications of policy decisions in one sector on other sectors in the Water-Energy-Food-Land-Climate Nexus[18].

8 The move towards a **probabilistic approach** rather than a deterministic one in modelling. The probabilistic approach is becoming more common in society, specifically with policy-makers and regulators. Well known examples in the Netherlands are the current approaches to flood-risk and local climate change scenarios. It is likely that in the future, a probabilistic approach will also be required by regulatory bodies worldwide. Simulations should include information on the uncertainty and/or variability of the input parameters, and be able to represent the simulation results in a similar way, rendering probabilities rather than (potentially false) certainties. The emergence of distributed computing resources, both on the desktop and in the cloud, now makes this approach feasible.

2.2 Hydroinformatics and smart water state of affairs

2.2.1 Hydroinformatics

HI has gained an increasingly prominent place in the water sector; today, few water-related projects can be executed without computer-supported design, modelling, analysis or optimisation. Furthermore, with increasing pressure on water resources and infrastructures globally, HI is increasingly called upon to provide the tools to deal with the issues resulting from, amongst others, ageing infrastructure, ageing workforce, over-exploitation of resources, pollution, increasing world population and climate change.

Despite the fruits of HI being ubiquitous in today's water management, the term HI is known only to a relatively small audience, primarily in the research community. The reason is the fact that, although HI provides the tools and methodologies, the results and insights obtained by its use are primarily communicated as being part of disciplines such as hydrology, water resources management, asset management, etc. Also, practical applications are generally offered as smart water solutions (see below). Therefore, the impact of HI is not always clearly recognised.

2.2.2 Smart Water Management

Smart water was at first primarily associated with using sensors to monitor water quantity, quality and detect leaks in drinking water distribution networks. It has gradually expanded into all areas of the water cycle. SWM can be

[16] Novak et al. (2016) Behaviour change and incentive modelling for water saving first results from the SmartH2O project. https://pdfs.semanticscholar.org/ae17/0368f99295f2610504e521c3ee0ab6d73a98.pdf

[17] Savić et al. (2016) Serious Gaming for Water Systems Planning and Management. https://doi.org/10.3390/w8100456

[18] Sušnik et al. (2018) Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy- Food-Land-Climate Nexus: the SIM4NEXUS Approach.doi.org/10.3390/w10020139

used for planning and operational purposes, from daily use to organisational and policy planning at a range of scales, across contexts (linking to smart cities) and regions.

As the need to adapt business to the reality of changing environmental conditions increases, the benefits of a more flexible, adaptive smart water system are becoming apparent, and adoption will rise. With reducing non-revenue water as the initial drivers, increasing resilience, optimising power consumption and customer interaction (both to improve services as well as influencing water consumption patterns) are increasingly important reasons to adopt smart water technology. Issues that remain, and which need to be addressed before SWM can fully fulfil its promise, include management of the overwhelming amounts of data that can be generated, standardisation to ensure interoperability between solutions, and making the systems (both physical and ICT) future-proof (resilient).

2.3 The perspective from the EU

The European Commission has named ICT technology as a key enabler to improve water resources management and address the water-related challenges by the member states. An impact is expected especially regarding monitoring and reporting quality, quantity, reuse of water, extreme events, smart decision-support systems, leakages and awareness of the true value of water by all stakeholders[19]. Through various initiatives, from amongst others DG Connect and WssTP, visions on the future role of ICT in the water sector have been developed,[20,21] focussing on a digital single market for water services. In this market, the water sector will be smart and resource-efficient, using networked, intelligent systems to make better use of energy, avoid unnecessary water losses and minimize the consumption of resources. However, despite the promising technological scenario, currently, the water domain is characterized by a low level of maturity and/or adoption concerning the standardization of ICT solutions, their business processes and the related implementation in the legislative framework. This is due to the fragmentation of the sector, the absence of a holistic vision, and a lack of integration and standardization of technology. The key challenges identified are the development of system standards to ensure interoperability of solutions, i.e., adaptability of solutions to new user requirements and technological change, as well as avoidance of entry barriers or vendor lock-in. On behalf of DG Connect, the ICT4Water cluster developed an ICT for Water roadmap for the EU and an action plan to tackle the key challenges.[19] It must be noted that the ever-changing ICT landscape must also be mentioned as it poses a continuous challenge.

2.4 In the Dutch Water Sector

2.4.1 Drinking water utilities

HI already started to gain ground in the Dutch water sector in the early 1990s with the application of the first hydraulic models. At water utilities the use of HI tools has become increasingly commonplace and is expected to grow further with the transition towards fully data- and model-driven operations. Nowadays, hydraulic models, SCADA, GIS systems, and asset management decision support tools are commonplace HI applications, and are integrated into the daily operations at the Dutch utilities. Also, monitoring and control of water treatment plants has been automated to such a degree that many of them run unmanned, at least outside office hours.

The drinking water utilities mostly rely on ‘conventional’ software applications to plan or adjust (the capacity for) drinking water supply infrastructure and maintenance, local sensors and actuators (SCADA), to operate water intake, treatment and supply processes. A frontrunner amongst the water utilities with respect to smart water is Vitens, which has, through initiatives and projects like the Vitens Innovation Playground, SmartWater4Europe and

[19] DG Comm (2018) Digital Single Market for Water Services Action Plan: doi:10.2759/724173 (available from: https://ec.europa.eu/futurium/en/system/files/ged/ict4wateractionplan2018.pdf)

[20] https://www.ict4water.eu/wp-content/uploads/2015/10/ICT4WaterRoadmap2016_final.pdf

[21] http://wsstp.eu/wp-content/uploads/sites/102/2017/01/WssTP-SIRA_online.pdf

Friesland Live, been experimenting with the creation and use of smart drinking water networks. This includes, for example, the installation of many sensors in the distribution network and the application of basic anomaly detection in flow data for burst detection. Building on these initial experiences, a lot of work has been done to assimilate live sensor data into hydraulic models. Evides has been pursuing similar goals in a slightly different manner, by creating what they call distribution islands (which are essentially large DMAs (district metered areas)) that are monitored in terms of flow and pressure. Furthermore, Waternet (and KWR) are involved in an EU project[22] to demonstrate the effectiveness of FiWare, an open source platform for data exchange and (smart) context-aware data management within a treatment line of the wastewater treatment plant Amsterdam West to improve operational performance. These are just some examples of the initiatives that Dutch water utilities are taking in this field.

Developments in areas such as anomaly detection, smart metering, AI for system modelling and automation, datamining of water (quality) data, and inspection drones, have been adopted by a few (Dutch) water utilities, but not all. The efforts to adopt HI concepts are not coherent, and data and solutions are fragmented. Indicative of the situation in the Dutch drinking water sector, is the absence of a flagship smart water initiative, e.g. as part of a smart city, where the possibilities of HI have been demonstrated in an integrated manner. In many other countries, such as South Korea, such initiatives are used to develop smart technology, including HI, and applied in systems such as Busan smart city, Daejun and YoungWol/Jungsun.

Many utilities have started to take the collection and storage of data more seriously, by setting up data warehouses or data lakes. Data quality and validation remains an issue in many cases[23], but this is an issue that can be tackled, as is shown by e.g., Oasen[24]. The potential of datamining techniques with the drinking water utilities has long been recognized, and been the subject of a number of BTO research projects[25], but concrete applications remain relatively rare. The advent of (start-up) companies specialized in datamining services and the increasing competences in this field with established research institutes may help the utilities in realising this potential.

Molecular Microbial techniques (Metagenomics, transcriptomics, next generation sequencing, whole genome sequencing, etc.) are starting to generate great amounts of data for microbial monitoring. Water utilities see potential but they are just at the start of interpretation of these data. Data handling, compression and storage is challenging and at the moment we do not fully understand which data are important and which are not. Also, the tools and databases for interpretation are still at the starting point of development, such that the chosen approach may impact the conclusions.

2.4.2 Water systems and wastewater applications

Concrete HI applications can be found throughout the entire water cycle. In the Netherlands, stakeholders from all water-related domains employ HI, for example, for management and control of assets, scenario and model studies, for decision support, for design and planning of systems, etc. The Netherlands has a number of frontrunner organisations with respect to the application of HI. Below are a few examples of these organisations and how they employ HI, related products and services, and what can be achieved with these applications.

2.4.2.1 Water Authorities

The Dutch water boards are responsible for the management of the (smaller) surface waters in the Netherlands (quantity, quality), flood protection and (part of) wastewater collection and treatment. Furthermore, they have a groundwater monitoring and management responsibility. As part of their day-to-day operations, they operate facilities through (increasingly) automated and centralised systems. Also, as part of their monitoring tasks, they

[22] See the project page of FiWare4Water for more details: https://sc5.easme-web.eu/?p=821036.

[23] see e.g. BTO 2019.011 Data validation.

[24] BTO 2019.041 VO datamining implementation pilots

[25] e.g. BTO 2016.007 Data mining for asset management and BTO 2018.085

collect large amounts of measurement data from manual measurements, laboratory analyses and increasingly sensors. Such data are often collected in central data repositories. Also, some water boards have created central control rooms for the management and control of their assets. These are typical applications of HI and smart water.

In the majority of the cases, water boards rely on external parties, such as engineering firms, ICT service providers and system integrators, to provide them with these solutions. Furthermore, they have organised various ICT and data services collectively through Het Waterschapshuis and Informatiehuis Water[26]. The latter organisation is, amongst others, responsible for the definition of common data models, data storage and exchange services.

Examples of recent projects include:

- Wetterskip Fryslân: management of groundwater data in a central information system (Dawaco) provided by RH/DHV;
- Waterschap Vallei en Veluwe: setting up of a central control room for all WWTPs;
- Open Water Data: providing data to the public through open interface. For example, groundwater level data through Lizard in web interface (HDSR).
- Predicting wastewater flows for design and dimensioning purposes (Geo-Dyn pro);
- De Dommel: Expert system Ecological Effects – an analysis tool to evaluate WFD measures on ecological and chemical quality of surface waters.
- A collection of tools developed by and for the water boards is available through the website waterwindow.nl.

2.4.2.2 Rijkswaterstaat

Just like the water boards, Rijkswaterstaat has a responsibility for water quality, flood protection, and monitoring of water quality. Rijkswaterstaat is in particular responsible for the larger inland waters (rivers, lakes, larger canals) and well as coastal waters. Measurement, storage and presentation of water-related parameters (both concerning physical and quality parameters) are a central part of the tasks of Rijkswaterstaat. Many of the results are reported through the Rijkswaterstaat website (e.g., water levels, wind, water temperature, wave height, discharge), but also a range of water quality parameters as measured at the border crossings of the rivers Rhine and Meuse[27]. Rijkswaterstaat is also responsible for the operation, maintenance and design and construction of the infrastructure related to these waterways (including dikes, bridges, and locks) and uses extensive modelling and optimisation tools in relationship to these tasks. Rijkswaterstaat also supports the government's open-data policy, and offers geographical and water data for public use, making data available through web interfaces as well as in various file formats.

2.4.3 Engineering companies and technology providers

A characteristic of the Dutch water sector is the large number of small, medium and large engineering and consulting companies active in the domain. These companies are typically involved in design, management and optimisation of assets, as well as assessments and simulations. As such, HI lies at the core of the water-related services offered by these companies. An overview of Dutch companies with a particular HI focus is provided in Appendix I.

2.4.4 KWR

KWR has a strong background in hydroinformatics and has over the years has built a track record through its HI projects executed together with its shareholders and BTO partners, the Dutch and one Flemish drinking water utilities. An overview of KWR's HI experience and expertise is provided in Appendix II.

[26] https://www.informatiehuiswater.nl/index.html

[27] https://www.aqualarm.nl

3 Vision for hydroinformatics and smart water

3.1 HI and SWM vision for the Dutch water sector and beyond

A digital transition is taking place all over the world – a transition that also affects the water sector. More and more is being measured, and measurements are being made more and more often. They are also being made at more locations, and things can increasingly be measured by anyone (or anything). Hydroinformatics involves established and developing technologies and methods which, on the one hand, help cope with or enable this digital transition and, on the other, exploit the opportunities it opens up. In this context, we already pointed in the introduction to the challenges that the water sector faces in coping with developments, such as population growth, climate change, urbanisation and migration, chemicals of emerging concern, and ageing infrastructure. We believe that HI and SWM can play a significant role in meeting these challenges by improving the efficiency and resilience of water infrastructures and by aiding in sustainable water management.

In this chapter, we present a twofold vision. The first aspect constitutes our vision of a smart water system in 2030. It provides a basis for the second aspect, which is our vision on how KWR can actively contribute to developing and adopting HI and smart water application concepts. These concepts are focused on providing insights and control in intelligent water use and reuse. Our vision of a future water system is of course presented as a possible outcome rather than an inevitable one. In other words, we describe the direction in which water management could develop in case our envisioned research, development and application of HI and SWM is adopted by the water sector and becomes a reality. The vision consists of an extrapolation of current developments, the integration of established technologies, and the introduction of additional elements which are yet to gain ground in the water sector (or, indeed, in the world at large).

Figure 3.1 provides a graphical representation of our vision.

The vision focuses on drinking water and wastewater, and other parts of the water cycle that are directly associated with this use of water. The main reason is that KWR has its history in drinking water, from source to tap – this is what we know best. That is not to say that the fields that have received somewhat less attention in this document are less important or do not stand to gain from the application of hydroinformatics methods; not in the least.

3.2 HI applied to the water cycle

Our vision of the digitised water cycle and our vision on applying HI is summarised in Figure 3.1. This figure depicts the various possible roles and applications of HI. In this figure the following dimensions are represented:

The first dimension is characterized by seven domains in the water cycle, representing the distinctive functions of water, namely:

1. sources (groundwater and surface water, environment and hydrology);
2. drinking water treatment;
3. drinking water distribution;
4. consumption and customers;
5. transport of wastewater or used water;
6. wastewater treatment;

7. water use and reuse in energy grids, food and industry.

Besides these domains, water safety can be seen as an additional, overarching domain, as well as system-wide approach that studies (possibly connected) water system infrastructures to e.g. optimise its resilience. The afore mentioned domains largely coincide with the organisational structure of KWR, in terms of research teams and themes (Figures 2.1 and 2.2). The teams within the Water Quality and Health Research Group, as well as the Resilience Management and Governance team address specific topics within each of these domains. The Industry, Wastewater and Reuse team operates in the last three domains, together with experts of the Geohydrology team and Drinking Water Treatment team. We elaborate on HI enabled scenarios for each domain in Section 3.2.1.

The second dimension consists of the HI components of modelling, data and information management, data analytics/mining, optimisation and control, visualization and adoption of HI in finished tools and concepts, which can be used for analysis, design and decision support (Table 3.1).

In the third dimension, three levels are discerned at which HI is deployed and managed by water utilities and other actors in the water cycle: the operational, tactical and strategic levels. The names and definitions of these levels are taken from asset management, are associated with different types of interactions, ranging from data and information management, to decision support and optimal control.

a) The operational level is characterized by the acquisition and processing of data through statistical and other models, the assimilation of these in system models, and the feedback of control decisions to actuators. The relevant scale is that of the subsystems of each of the six domains described above.

b) The tactical level deals mainly with questions of design of water (related) subsystems and measurement/sensing systems, including (failure/anomaly) scenario studies, and rehabilitation decisions. This works mostly at the scale individual domains or parts thereof.

c) The strategic level transcends domains and encompasses integral concepts, for example, comparisons of different source scenarios, management of water production and energy (storage) systems, or monitoring, control and governance of a decentralized water supply system.

Figure 3.1 depicts the different domains and their interrelationships. It shows how data and information flow between these domains depends on the level of application (operational, tactical or strategic), and how these information flows are technically embedded.

The next sections elaborate on the first, domain-oriented, dimension and on the interaction of the operational, tactic and strategic levels in the second dimension.

Table 3.1: Overview of the classification of hydroinformatics technical components shown in Figure 3.1. Note that the Application component is not mentioned explicitly in the figure, but is represented by the field in the centre. Decision (support) systems form a key aspect of the Application component.

Component	Description
simulation	Deterministic or probabilistic digital representation of a system or process, which predicts the state of a parameter or group of parameters in the system or process, as a function of values supplied for the parameters, based on understood physical or technical relations.
data validation and management	Activities that support the validation, verification, infilling, labelling, organisation, storage and dissemination of data.
data analytics/mining	Statistical or machine learning interpretation of data.
optimisation and control	The addition of a meta-layer to numerical process/system models, to generate optimal configurations or controls.
visualisation	Human readable representation of data and/or models, virtual/augmented reality.
application	The adoption of HI in finished tools (scripts, software), and application of HI to operational control, tactical and strategic decision support.

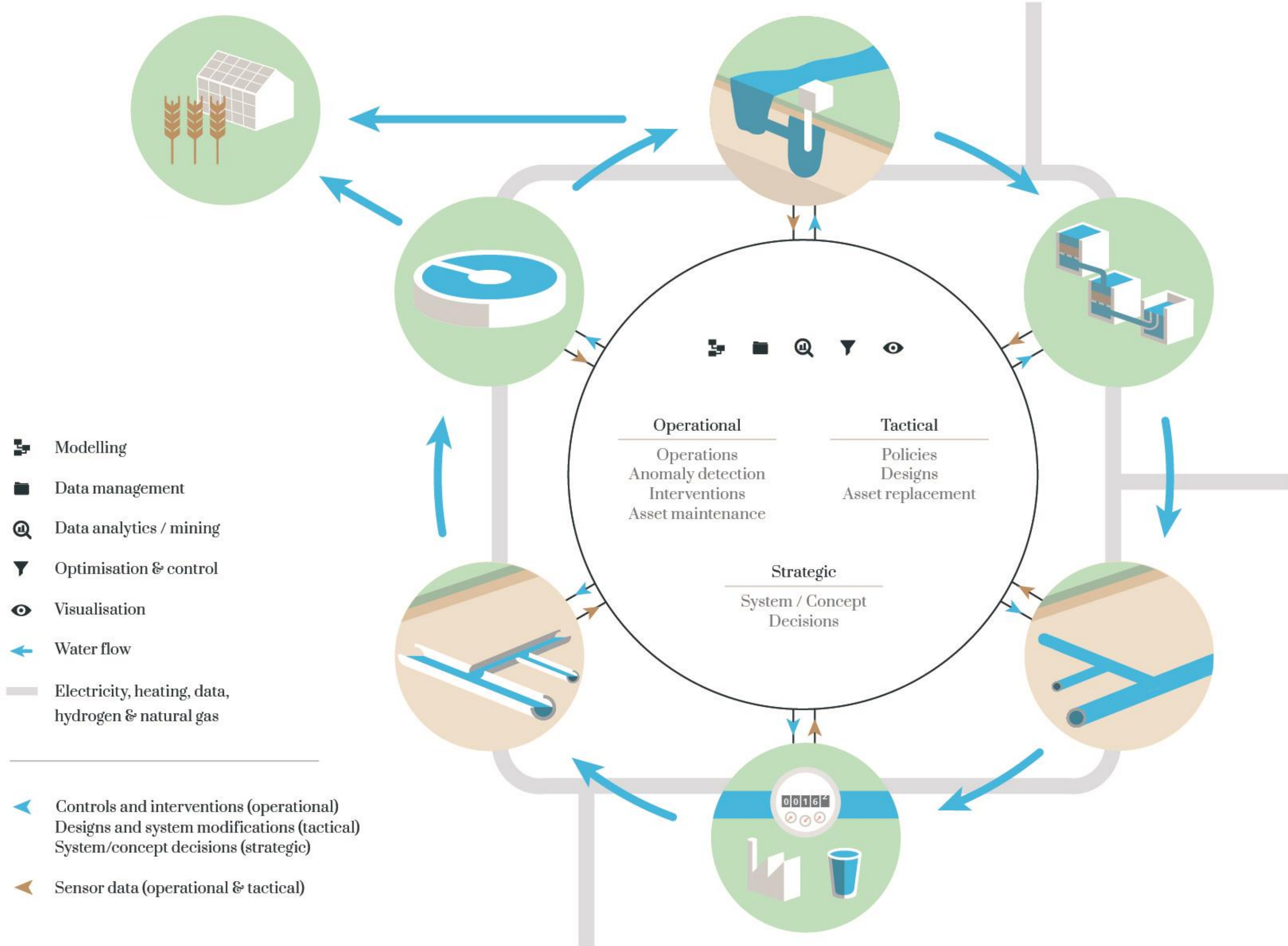

Figure 3.1: Schematic representation of the vision on the role of HI and SW in the Dutch water sector. This is a simplification of a more elaborate picture, which is presented in Appendix III.

3.2.1 Domain perspectives

This section provides an overview and description at a domain level. We provide an overview of our vision for each of these domains in the European context, over a 10-year time horizon:

- Water sources and storage in the subsurface. The subsurface provides one of the major water sources, groundwater, for drinking water production, as well as for agricultural and industrial use. In addition, the subsurface is increasingly used for the storage of water from a range of sources, such as rainwater and treated wastewater, in an effort to both cope with increasingly variable water availability and make water production more sustainable. A range of spatial scales are involved in the use of the subsurface water production, from the delineation of recharge zones, to the abstraction and infiltration of water using wells and drains. Optimisation, forecasting and uncertainty-control, using sophisticated modelling and sensoring (IoT) are applied to realise cost-effective and sustainable water resource management. For example, stochastic modelling techniques allow the quantification of uncertainty for recharge-area delineation and travel-time estimation, which is increasingly important given the increasing stresses and changes due other uses of subsurface and due to climate change. At this large spatial scale, the analysis of the relation between vegetation and evapotranspiration, which affects groundwater recharge, is also aided by remote sensing techniques, like satellite imaging and unmanned aerial vehicles (UAV), for near real-time monitoring in support of groundwater management strategies. In addition, decision support systems, and even fully autonomous control systems, optimally operate groundwater wellfields in line with water demand, water-quality requirements and minimal energy consumption. At the scale of individual wells and drains, the combination of (remote) sensing data and near real-time glass-fibre based distributed temperature sensing (DTS) and conductivity, allows the optimisation for example of well performance for recovery, production and clogging prevention. Finally, the fact that water sources are influenced by many third parties, makes access to the data (operational and observational) of these third parties relevant for the management and exploitation of these sources, and important for inclusion in simulation models (including digital twins) and (big) data analyses.
- **Drinking water treatment.** The operation of drinking water production is heavily automated. Quantity and quality control of drinking water is achieved by controlling process operational parameters during treatment – like flow, pressure and pH – and through (off-line) monitoring of the water quality of the source and produced water. Direct near real-time monitoring and prediction of water quality has become standard practice. This is based on a robust combination of sensitive but reliable sensors that can capture the microbial and chemical fingerprints; data assimilation techniques; and artificial intelligence, which relates fingerprint features with treatment characteristics and the optimal operation of treatment processes. On a tactical level, decision support systems provide information about the vulnerability of treatment technologies to compounds of emerging concern, using advanced statistics, artificial intelligence and process modelling (e.g., through QSPR[28] models). Risk assessment tools, in turn, provide information on microbial and chemical risks. Augmented reality and predictive analytics are used for maintenance and process quality control, and computationally intensive models can be run in the cloud to optimise treatment process designs and assess the performance of whole treatment plants. Strategists at water utilities can take decisions concerning resilient water supply more easily, thanks to scenario tools that integrate the condition of water sources, treatment characteristics and forecast water demand under different stresses, such as weather and climate scenarios and pollution.
- **Drinking water distribution (DWD).** Anomalies are detected using models (digital twins) supplemented with data analytics. Operators, in conjunction with autonomous decision (support) system, can identify water-quality issues in near real-time, and, using remotely operated valves, prevent these issues from ever reaching a customer. This results in real-time control of the system that delivers water to the customers. Also, water quantity anomalies are interpreted in terms of gradually developing of sudden bursts and leakages.

[28] Quantitative Structure Property Relationships are defined in Showcase 2 of Table 2.2.

Operators, in conjunction with autonomous decision (support) systems, direct field operatives to conduct preventive or remedial maintenance before customers notice there is a problem. This contributes to communicating an image of full control by the utility to its customers. In DWD networks, inspection robots continuously inspect the network, visiting each location twice per year and measuring pipe wall condition and pipe location, as well as identifying and localize leakage or inflow. The resulting data, combined with asset condition sensor data and additional sources, give a complete picture of the installation or network condition in drinking water distribution and wastewater transport, which is always up to date (i.e., at most, 6 months behind, which is a very usable timescale).

- **Water Quality** is monitored by broad target and non-target screenings to find known as well as new unknown substances (in particular compounds of emerging concern). Sampling methods are moving increasingly toward real-time provided measurement data, such that only few laboratory analyses are needed. Rapid, automated, molecular based analysis (sensors) continuously protect against unexpected contamination. Advanced molecular methods monitor the microbial community to signal 'unhealthy' conditions. Mixture effects and transformation products are predicted and assessed. Sophisticated and well validated bioassays confirm that nothing harmful is missed. Prediction models guide the screening strategy for each location of interest. Screening data (which can be in petabytes) are stored centrally and processed according to standards, safeguarding interoperability of results, for example, for water laboratories and Water Authorities. In other cases, data are harvested from external sources. Data are used as input and for valorisation in decision models. Risk assessment for known and unknown substances of concern is done using prediction models based on (chemical and physical) properties of contaminants, and works according to the 'one health' principle (integral risk assessment).
- **Consumption and customers.** Customers (industrial and private) are both a continuous source and a continuous sink of data. Developments such as the smart phone, apps, and social media enable customers to measure, send and receive current information. For instance, they can be alerted quickly to disasters like excess of water on the roads, or be reassured about the strange colour of their drinking water. Water utilities can be alerted to problems by automatically monitoring social media. Customers provide flow, pressure and water-quality data from their smart meters and receive notifications on works and water-saving achievements. This knowledge increases awareness and engagement, which can lead consumers to manage their water use, thus saving energy and resources. Gamification also provides a means to get customers involved in water-related issues. Social scientists with marketing expertise are involved in making this transition. Compliance to the European general data protection regulation of this consumer data is arranged by having correct processes, policies and infrastructure.
- **Transport of wastewater or used water.** The water infrastructure has direct and indirect connections to other sectors. The direct ones include data networks used to monitor and control water infrastructure, or the recycling of materials from water treatment. The indirect connections are apparent, for instance, when the failure of one sector's infrastructure affects that of another because of their proximity – for instance, when agriculture is affected by a water shortage, or when energy networks are switched off by cyber-attacks). Weather predictions and river flow models are coupled to sewer models, and optimal predictive control schemes to minimise sanitation sewer overflows; and sewer inspection robots send their data to a cloud environment, where detection algorithms and predictive analytics are run, with results being sent to wastewater treatment plant control algorithms.

Wastewater-based epidemiology, which consists in mining the chemical and biological information contained in wastewater, makes it possible to obtain, almost in real-time, data about the health and behaviour of communities at a high spatial and temporal resolution. Mining the information of wastewater relies on the use of advanced chemical and microbiological analytical tools, such as non-targeted screening using mass spectrometry and Next Generation Sequencing, respectively. These tools generate enormous amounts of data that need to be processed and interpreted in a structured and robust framework, which relies heavily on informatics, data science and sophisticated machine learning tools. Mining the chemical and biological information of wastewater has matured, using an integrated approach which includes epidemiological, demographic, environmental and urban data. This allows for the development of surveillance tools to help improve human and environmental health.

- Wastewater treatment. A complete picture of water quality in wastewater treatment is generated by data fusion techniques, and used by advisory and/or semi-autonomous decision systems which support operators in identifying anomalies and improving control processes in the WWTP. Full-scale wastewater treatment plant control allows for optimisation of multiple objectives, such as high effluent quality, low energy consumption, treatment costs, low greenhouse gas emissions and high revenues from the harvesting and upcycling of materials. Sophisticated models connect the various elements, such as settling, biological processes – e.g., activated sludge, Anammox, sludge treatment (digestion, dewatering) – and post-treatment, with the aim of removing emerging compounds. More data on water quality and quantity in receiving waters and groundwater are being collected to evaluate the effectiveness of emission policies, and to facilitate data analysis studies and the development of decision support systems. Further development and application of decision support systems regarding the abatement of emerging compounds are aided by advanced statistics and artificial intelligence techniques, as in the case of QSBR[29] modelling.
- Water use and reuse in industry, energy and food.
  In horticulture and agriculture, both the availability and quality of water are important for optimal crop yields. The mismatch between supply and demand leads to the need for storage. Lack of space, salination of groundwater and evaporation losses are drivers for adopting subsurface water storage and reuse of water, in farmer corporations where possible. Advanced monitoring, forecasting techniques and (model predictive) control guarantee the availability of good quality (in chemical as well as microbial composition) irrigation water, and zero emissions of micropollutants and nutrients. Analogously to the drinking water production case, the design, evaluation and risk assessment regarding treatment technologies and the removal, or even recovery, of crop protection products and nutrients, is aided by artificial intelligence and advanced statistics that rely on molecular and physico-chemical properties of treatment barriers.

  Likewise, the availability and quantity of water in the process industry are essential for industrial operations. Water can be part of the production process, an ingredient, a means of cleaning, an energy carrier (heat), or a means of cooling. Tailored models and tools for the design of water reuse cycles, minimisation of water use, life-cycle analysis, predictive models and augmented reality will play a major role in improving the footprint of an industrial process, quality control and maintenance. The energy transition in particular has significantly increased the role of water as a carrier and storage medium of heat, and therefore also the role of these hydroinformatics concepts in their planning, design, operation and asset management. On the operational level, models and data fusion algorithms are equipped with artificial intelligence and domain knowledge, and form the basis of model predictive control schemes to optimise objectives in water reuse, energy, effluent or (demineralised) water quality.

  Water and energy management are driven by optimal model predictive control (MPC), such that each of the different objectives of various stakeholders are met efficiently. For example, to guarantee optimal and reliable allocation of energy resources throughout the year, MPC driven energy management systems consider the availability of various renewable energy resources and green hydrogen, stochastic (consumer) demand, electricity tariffs in the energy market, the predicted capacity of aquifer thermal energy systems (ATES), and the variable nature of weather and seasons. Water is also a critical component for the energy transition, for example, through its high-thermal capacity, and as a resource for green hydrogen through electrolysis. For example, the subsurface storage of thermal energy in ATES systems, optimisation of energy recovery and recovered temperature levels are being supported by advanced modelling, such as agent-based

[29] QSBR: Quantitative Structure Biodegradability Relationships describe the statistical relation between a (rate of) biodegradability and the chemical-structural properties of (emerging) compounds. QSBRs are mathematically equivalent to QSPRs.

modelling. This also supports the development and implementation of performance forecasting and model-predictive control, for example, for the operation of district heating networks that utilize ATES systems for heat storage.

- Water safety. Monitoring the increasing number of chemicals and assessing their effect on health and the environment, including the effect of metabolites and mixtures, in particular for compounds of emerging concern has become a mature, acknowledged and endorsed part of the safety procedures. This is facilitated by the application of several water-quality analysis methods that are moving towards near real-time analysis, including non-target screenings and bioassays to detect both known and unknown substances, and assess their effects on health, and molecular techniques such as PCR[30] and NGS[31], which are fast and provide detailed information about the microbial water quality.

  Both chemical and microbial analysis produce a vast amount of data per analysis. Interpretation of these data is based on reference databases and datamining techniques. Risk assessment for known and unknown substances of concern is done using prediction models, based on (chemical and physical) properties of contaminants, and work according to the 'one health' principle. Rapid, automated, molecular based analysis (sensors) continuously monitor for contamination. Advanced molecular methods monitor the microbial community to assure 'healthy' conditions. Prediction models guide the screening strategy for each location of interest. Screening data (which can be in petabytes) are stored centrally and processed according to standards, safeguarding interoperability of results, for example, for water laboratories and Water Authorities. In other cases, data are harvested from external sources. Shared databases are used for interpretation, and newly obtained data are added to share with others. Data are used as input and for valorisation in decision models.
- System-wide perspective. Resilient infrastructure that is apt to meet future challenges (urbanisation, population growth, migration) and uncertainties (cyber-attacks, climate) have to be designed with care. Simulation or statistical models, fed with (experimental) data, and scenario modelling aid this. For example, digital twins are used for supporting governance processes such as town planning and replacing documents with legal status, such as zoning plans. Systems need to be 'smart' and be designed to respond in the correct manner to changes. Decisions on the replacement of pumps, pipes, sensors, actuators, or other system components, are made by asset engineers who draw on comprehensive asset condition information which is provided by data and decision support systems. This allows the water utility to replace the right component at the right time – both in terms of economics and customer satisfaction. Decisions on system-wide concepts that encompass all components – such as centralized vs. decentralized water supply, or small scale vs. large-scale urban heating networks – are made by subjecting a complete system model to a multitude of scenarios, giving decision-makers an optioneering tool to identify the best options. This leads to robust system decisions based on sound, quantitative information. The effectiveness of whole systems can be further tuned by dedicated data-driven decision support systems and numerical optimisation. A quantitative consideration of uncertainty in measurements, models and results is an inherent and essential part of this approach.

3.2.2 Data networks as the gluing component of hydroinformatics

Data can amount to vast volumes, can be subject to change, and can have different structures and formats. Data are in some cases centrally stored and in others harvested from external sources. Text mining is one of the methods of harvesting (semi) unstructured information. Data are processed according to standards, safeguarding interoperability of results, for example, between water laboratories and Water Authorities. Data are used as input and for valorisation in decision models. Access to data is managed by appropriate access rights, enforced by the

[30] PCR: Polymerase Chain Reaction: a technique that amplifies DNA sequences by the use of (polymerase) enzymes, such that these sequences can be subsequently detected and identified.

[31] NGS: Next Generation Sequencing: sequencing methods which are highly scalable and allow the identification of a whole genome at once.

infrastructure. There are many sources of data that span wider geographical areas, and these are used as a source of information as well, where relevant. Using European or even globally available data enlarges the knowledge base and makes results (models, scenarios) more transferable beyond the Netherlands.

3.2.3 The operational, tactical and strategic levels

Central hydroinformatics themes at all three levels (operational, tactical, and strategic) are data management, cybersecurity and system models. On an operational level, these are supplemented with lab analyses, soft sensors, data assimilation, pattern recognition and anomaly detection algorithms, as well as advisory and autonomous decision (support) systems. At the tactical and strategic levels, incident and/or scenario generation and simulation are added to the mix, as well as autonomous design systems and optioneering tools, respectively. Finally, in each system that is built for direct interaction with humans, visualization of data, models, and actionable information is an additional key component. There are several ways in which these components manifest themselves. System models that assimilate real-time data may be considered digital twins. Visualisation is a broad term which covers tools ranging from simple graphs to augmented and virtual reality. Virtual and Augmented Reality combined with interactive modelling/optimisation (with the operator in the loop) can also be part of this.

As mentioned above, the operational, tactical and strategic levels share centrally maintained data management and system models. Essentially, these contain information on how the system is built and how it behaves, which is applied to problems/questions arising at all three levels. The level of detail required may vary, generally decreasing from the operational towards the strategic level. Operationally acquired and interpreted data may lead to improvements in the system and/or the system model, which may be fed up to the tactical and strategic levels. On the other hand, designs and interventions devised at the strategic and tactical levels feed down towards the operational level in changes in layout and operation of the system.

3.2.4 General benefits of the envisioned water cycle

The integration of existing and upcoming systems as described previously, leads to a data rich environment, in which all information necessary to make informed decisions on current issues, and predictions on the future state and operation of the system, is available. This is in stark contrast to the present situation, in which information on the state of (buried) assets and quality of water at most times and locations is unknown/unverified. This future situation of information richness is expected to lead to higher quality decisions at each of the three levels of decision-making (operational, tactical, strategic), since unknown parameters that may affect the outcome will have been eliminated. The result: better concept choices, better system designs and better operations. In this context, better may mean more effective, more efficient, cheaper and more reliable. This will help make the water cycle better equipped to cope with its future challenges.

3.3 KWR's position within this vision

In Chapter 2, we described how digital technology is transforming the way the water sector operates. This transformation is enabled, and its pace is accelerated, by trends in society. In the preceding sections, the scope of HI and smart water management is described in view of different dimensions: a domain-oriented one, the level of implementation within an organisation, and the technical manner in which HI concepts are integrated in digital infrastructure. KWR has historically been at the basis of or involved in many developments in the Dutch water sector, and now it needs to be at the forefront of digital developments as well, if it is to remain relevant. With ever-growing volumes of data and more advanced analysis technologies, new insights and solutions continue to emerge. Harnessing the possibilities of new technology demands state-of-the-art utilisation of HI.

KWR's main focus remains the creation of knowledge on water and its application in practice. We do this in close collaboration with our partners and clients through a process of co-creation. HI has been an important pillar for KWR's core activities for more than a decade, but mostly implicitly. To remain relevant and keep this leading role, the application of advanced HI tools will be crucial for KWR. HI needs to become an explicit pillar of KWR's activities. This will make it possible to generate critical mass and focus where it is needed most, and to allocate resources in an effective way. With its in-house expertise in all facets of the water cycle, and the opportunity of combining this with its HI competence, KWR is uniquely positioned to develop integral and/or integrated solutions.

As part of KWR's dedication to pushing boundaries, we not only use proven HI methods, but actively initiate or pioneer innovations to assess how they can benefit the water sector. In this effort, KWR paves the way for the broader application of new technology in the sector. The expert knowledge and experience that KWR gathers with regard to these technologies is not only reflected in state-of-the-art solutions and tools, but is also used to support water utilities in the implementation and use of HI based technology.

Currently, KWR's HI and smart water products are primarily developed to serve their secondary role in projects, and are focussed on subsequent reuse by KWR and project stakeholders. Tools are developed to a level where they can be used and reused by the KWR organisation and provided to our partners and clients (e.g., through Watershare). Greater attention should be paid to the way these tools fit in and interact with the software ecosystems that exist at our clients', and primarily at the water utilities.

As the solutions and tools can be seen as calling cards for KWR, they have to be representative for the current state-of-the-art in software tools and applications (look and feel, user experience). Where possible, commercialisation of applications is being explored, for example, as spin-out initiatives or by third parties (e.g., Allied Waters).

In the use of HI and smart water, KWR's research activities focus on:

1. Tapping into the new data landscape. For example: data standardisation, data quality control and validation, improving data access (including data sharing and open data), big data analytics (including statistical summaries and novel visualisation), gaining new insights from of large, heterogeneous databases by knowledge discovery and datamining, developments in AI such as deep learning, as well as customer/citizen interaction and data crowd-sourcing.

2. Getting more out of data and models. For example: data assimilation (field data coupled with models and/or field data from different sources and with different uncertainties are used in combination), advanced optimisation (including smart model calibration under uncertainty and noise); model development and integration, with databases and other models, as well as with real-time data (including IoT sensors) to form 'digital twins' of water utilities.

3. Planning for more resilient (whole) systems and services. For example: model integration and higher abstraction level modelling/model coupling, whole system strategic models, forecasting and scenario planning tools, cyber-physical water system security, modelling of cascading effects between water systems and other infrastructures.

4. Training, engaging and communicating. For example: tools/methods like Serious Games, Augmented Reality, Virtual Reality, Immersive scenario planning (including crisis management training), but also more general questions like communication of results in terms of probabilities rather than certainties and decision-making in this context.

In these fields of activities, KWR strives to be at the forefront of the take-up and utilisation of innovations. This position is cemented by close cooperation with internationally leading research groups and technology suppliers. KWR actively pursues collaborative projects with these organisations. Also, KWR is actively involved in the formulation of (EU) policy and efforts to realise the digital single market for water.

4 Concluding remarks

The ultimate measure of success of HI and smart water - namely, implementing scientific, information-theoretic developments in practice, to benefit the water sector and society at large - depends on the strength of the following four pillars:

1. a secure, integrated data infrastructure connected to sensors and actuators, a data management solution, and the availability of - but also long-term support for - (software) tools or embedded software;
2. the employment of data scientists and hydroinformaticians, and the support of knowledge transfer, within and between water utilities and institutes;
3. support for research and development in HI, especially in areas where IT developments are not yet translated into solutions for the water sector;
4. the belief that smart water systems are able to meet today's and tomorrow's challenges.

The vision presented in this report is based on an analysis of the current state-of-play and of technology trends and identifies opportunities to be exploited and risks to be addressed in several contexts, including the BTO programme. A workshop with the BTO participants will be organised in September 2019 to discuss the vision and steps necessary to realise those aspects of it that the BTO participants choose to pursue.

5 Acknowledgments

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I Appendix - Engineering companies and technology providers

I.I Royal Haskoning/DHV

Examples of RH/DHV projects include:

- Smart asset supervision and maintenance for PWN.
- Two design projects for overland flow and storm water collection systems for Randwick City Council (AU). The project involved 2D TUFLOW hydrodynamic modelling using a 'direct rainfall' approach to assess existing flooding for a number of low-lying residential properties.
- Development of a smartphone app for community dissemination of flood warning and flood mapping information.
- Aquasuite® control software for process control. Used for control of WWTP, but also used by Vitens. Latest versions also include Big Data analysis and machine learning algorithms. Used for instance by Vitens and HDSR (for control of Utrecht WWTP).
- Development of a flood forecasting and warning system on the Sava river, in Eastern Europe. The Sava FFWS combines multiple numerical hydrological and hydraulic models to simulate the expected flows and water levels throughout the Sava river basin. It is built on the Delft-FEWS software, an open data integration software platform for operational water management and forecasting developed by Deltares.

I.II Witteveen+Bos

Another large engineering company with a strong focus on innovation, including simulation and modelling. Applications include optimisation of the wastewater collection system and WWTP of the city of Eindhoven (Kallisto project),flood warning, dam safety, groundwater modelling.

I.III Deltares

Deltares is an independent institute for applied research in the field of water and the subsurface. The institute operates globally, with a focus on applications for deltas, coastal regions and river basins. Modelling and simulations, as well providing practical tools for customers, are the central focus of the work at Deltares. This is reflected by the large suite of software tools for simulation, data collection and management, serious gaming, and others that is available through the Deltares website. Some of these are available free of charge, others are commercial products that need to be purchased. Deltares has a dedicated software development team and a model development team. The institute also organises the Delft Software Days, where experience and knowledge concerning the use of these tools is shared. Examples of Deltares products include:

- Delft-FEWS – flexible solution for data acquisition, management and modelling. Used by, among others, various water boards for storage of hydrological data, and as a hydrological forecasting and warning system. Delft-FEWS has also been applied in a wide range of different operational situations. Examples are
- water quality forecasting, reservoir management, operational sewer management optimisation, and even peat fire prediction.
- D-Hydro-suite – the application example is a well-documented study of the results of a breached levee in Rotterdam.
- DAM – assesses dike strength using D-Geo Stability engine.

I.IV Artesia

Time series analysis, data validation, modelling, software development (e.g., app for logging field measurements, SW for time series analysis, salt water intrusion model for MODFLOW).

I.V Technology suppliers

Another category of company active in hydroinformatics and smart water systems are the technology suppliers. These can be either hardware of software suppliers. As opposed to the engineering and consulting companies, that focus primarily on services and use hydroinformatics as a tool, the technology providers are primarily focussed on the sale of tools. Although all providers of automation and monitoring solutions are to some extent involved with aspects related to HI, in particular data acquisition, it is not necessarily their primary focus. There are however examples of companies that have a particular focus on water and information technology. Examples of companies that have hydroinformatics and smart water at the core of their business is provided below.

Hydrologic
A consulting company focused on the use of ICT to solve water issues. Their work revolves primarily around the applications of Hydrologic's own HydroNET software suite, which offers dashboards to display information made available through Delft-FEWS, Wiski and other data sources. Hydrologic's main objective is to present data in a way that it can be used by end-users at all levels, from manager to field-worker. Main clients: water boards, municipalities, provinces and research organisations.

I-real
A company focused on supplying infrastructure for the creation of the Internet of Things for water infrastructure. It provides hardware and software solutions for data collection, storage and visualisation, as well as control of assets. Main clients: provinces, water boards and municipalities.

Quasset
Quasset focuses on Asset Management and Condition Assessment. Its software tool, Q-Pro, offers tablet-based data capture and workflow management systems for inspection and maintenance, risk modelling and asset forecasting solutions. It includes web-based 3D visualisation software which efficiently creates digital twins of assets. It also operates the Quasset Test Facility (QTF) to facilitate the development of robotic solutions for inspection and maintenance activities.

IMD
IMD is a company specialising in monitoring of water quality and quality. Working for water boards and industry, it provides measurement services (from rental of sensors to performing complete measurement campaigns), and process optimisation based the measurement results. IMD has developed data collection and validation tools as well as dashboard software for visualisation of data. It also uses data analytics tools to extract information from monitoring data, in particular spectral information.

LG Sonic
A provider of systems to combat algal blooms. These systems use information from water quality sensors, weather data and satellite data to determine the optimal settings of the ultrasonic treatment buoys. LG Sonic has won several awards for what it calls its 'data-driven water treatment'.

ICT Group

A large general ICT company, which also provides smart IT solutions for Water Authorities, drinking water utilities and governments. For instance, IT solutions to remotely control and read installations and systems; or the use of the Internet of Things and big data to predict maintenance or malfunctions.

aquatune

The objective of aquatune, an engineering company, is to supply clients in the water sector (drinking water and wastewater) with support systems based on Artificial Neural Networks (ANN) and Genetic Algorithms (GA) technologies. The proposed values are well suited to minimize consumption of energy and operating resources, while safely complying with legal limit values of pollutants in the effluent. Thus, aquatune supports clients in solving the complex tasks of operating their plants.

II HI research at KWR

In its research KWR uses state-of-the-art information technology to generate new information and insights. This section provides an overview of HI research at KWR and illustrates .

II.I Experience and expertise at KWR

KWR has an extensive track-record of projects in which hydroinformatics concepts were employed. An inventory of ongoing projects and initiatives related to HI in the various KWR teams over the past five years has been made. The HI elements used in the assessment of the expertise and experience are briefly described in Table II.1. Figure II.1 provides a summary of these activities, while Figure II.2 shows the availability of HI expertise at KWR. In both figures, the projects and experience have been categorized with respect to the field of application and to aspects of HI.

Table II.1: Explanation of the elements of hydroinformatics used in the assessment of KWR expertise and experience.

Element	Description
Data acquisition:	The generation of data using sensors, polls, citizen science or other means.
Data validation:	The verification, correction, infilling and quality assurance of data.
Data management:	The structured storage and making available of data within an organisational structure.
Data analytics:	The application of statistical, Artificial Intelligence/Machine Learning or other tools to discover information in data.
Simulation:	The use of a digital representation of a (sub)system or process to predict an outcome of the system or process, given one or more inputs.
Optimisation:	The process, supported by numerical methods, of finding the best solution or set of solutions (design or operation of a system) to a predetermined objective, subject to constraints.
Applications	The adoption of HI in finished tools (either software that is sufficiently mature for application to water sector issues, but not in terms of user experience, sometimes called decentware, or market-ready software), and application of HI in operational control, and tactical and strategic decision support.

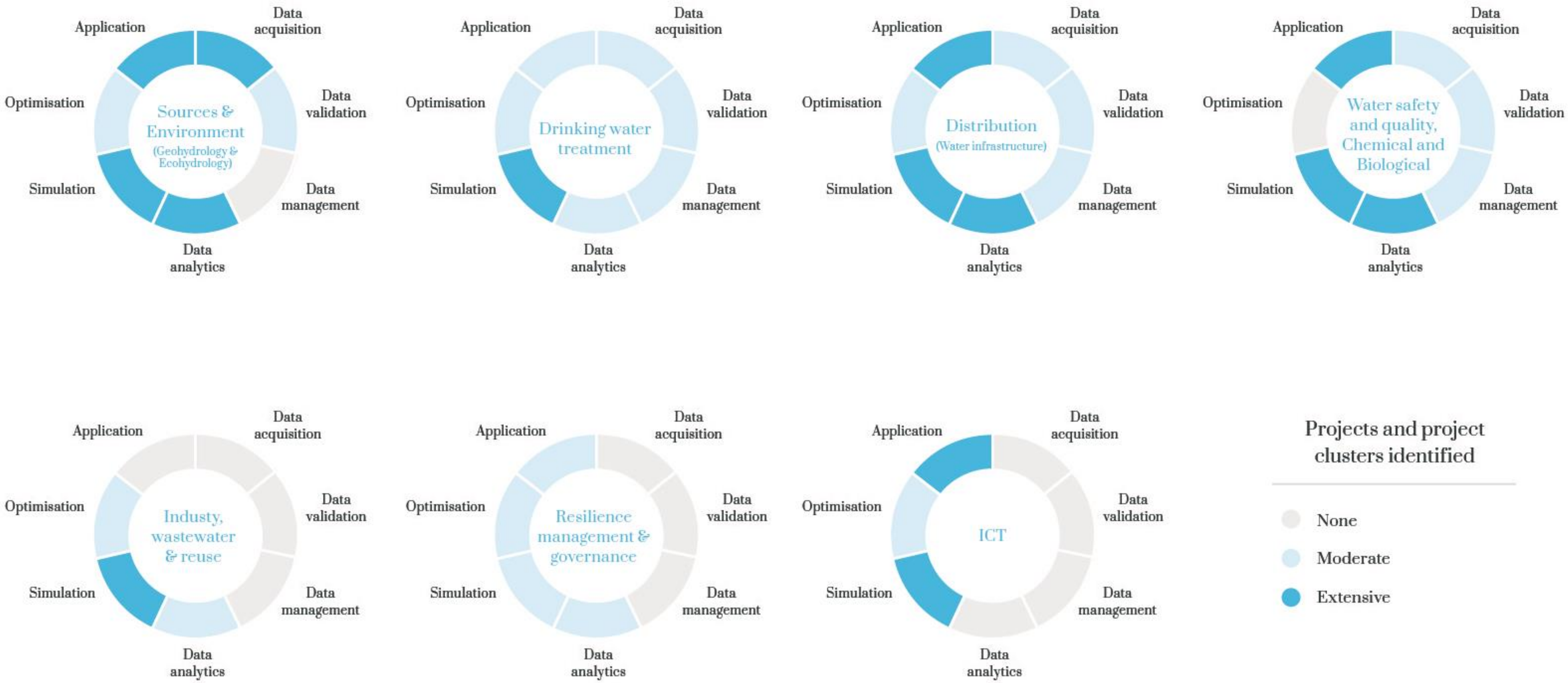

Figure II.1: Overview of HI focus areas in the various teams at KWR.

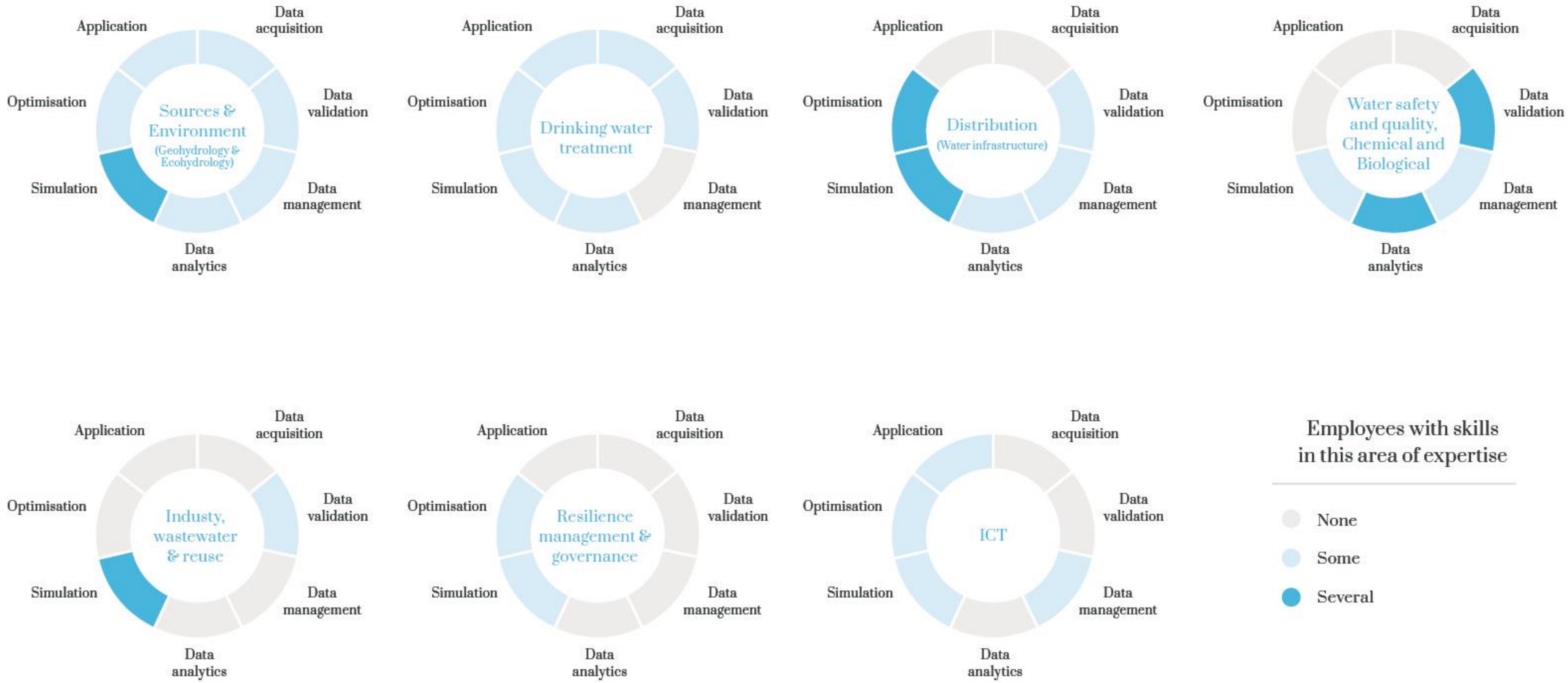

Figure II.2: Overview of researchers with HI capabilities in the various teams at KWR.

II.II KWR project showcase

To showcase the type of projects KWR is involved in, Table II.2 lists a series of recent and ongoing projects as illustrations.

Table II.2: KWR project showcase.

Showcase 1 - Big data in optimisation of drinking water treatment	
	Stored data on water quality parameters and operational parameters were used to train a model to predict pressure building in the sand filters in a coagulation process, followed by sand filtration. With this, the filtering time, filter rinsing frequency, and dosage of iron supplement could be optimised.
Showcase 2 - Predicting removal efficiencies for micropollutants	
	Mechanistic models of removal techniques are combined with QSPRs[32] to predict removal efficiency of any micropollutant for specificremoval steps.
Showcase 3 - Designing optimal water distribution networks	
	KWR has developed Gondwana as a generic tool for the numerical optimisation of the design and management of drinking water distribution networks. It has been successfully applied in the optimisation of network dimensioning, DMA design and transitions.
Showcase 4 - Scenarios to calculate effects of using or storing energy as heat or H_2	
	In Power-to-X, different scenarios are calculated to see what the most efficient options are for H_2 production and optimal heat production, subsurface storage of converted solar energy in financial terms, overall energy efficiency, and thermal impact on groundwater.
Showcase 5 - Smart water meters to map drinking water temperatures	
	Machine learning techniques were used to derive relations between the weather, the characteristics of the distribution network, urban environment and drinking water temperature.
Showcase 6 - Computational fluid dynamics (CFD) modelling	
	Understand the flows of water during drinking water treatment. This was put to use, for instance, in improving the design of rapid filters or the operational management of installations .

[32] Quantitative Structure Property Relationships, i.e., statistical relationships between structural characteristics of compounds and a physico-chemical property of a removal technique, like e.g. sorption capacity of activated carbon

Showcase 7- Resilience	
	The development of new, integrated water-wise concepts for the urban water system, including the software tools to evaluate them and their resilience. Examples of applications include looking at the centralised versus the decentralised water cycle, investigating the effects on system performance of modular water facilities and sanitation, developing scenario-based stress-strain diagrams for water system resilience profiling.
Showcase 8 - QMRA	
	Drinking water utilities intensively monitor micro-organisms in raw water and stages of treatment. KWR developed a QMRA tool to translate these data to probability distributions to perform Monte Carlo simulations to calculate health risk. Further work resulted in a database and the Watershare QMRA Treatment Calculator tool, and contributed to the WHO GDWQ Table 7.1.
Showcase 9 – Simulating peak water demand	
	SIMDEUM simulates household water demand per minute or even per second. This can aid in interpreting sensor data or predicting the influence of different scenarios, such as introducing water-free toilets. It can also assist, for instance, in the design of drinking water networks.
Showcase 10 - Retrospective analysis of raw MS data	
	Raw acquisition files from LC-MS analysis were retrospectively searched for newly emerging contaminants of concern, in order to assess the significance of new compounds for the water quality and/or to prioritise, e.g. toxicological evaluations.
Showcase 11 - Automated vegetation classification from remote sensing images	
	By using supervised classification algorithms, KWR is able to quickly transform raw hyperspectral images from earth observation satellites (e.g. Sentinel-II) and Unmanned Aerial Vehicles (UAVs) into useful vegetation or drought maps. This helps water utilities estimate evaporation fluxes and water authorities evaluate the efficacy of drought prevention measures.

III Appendix - Vision on the role of HI and SW in the Dutch Water Sector

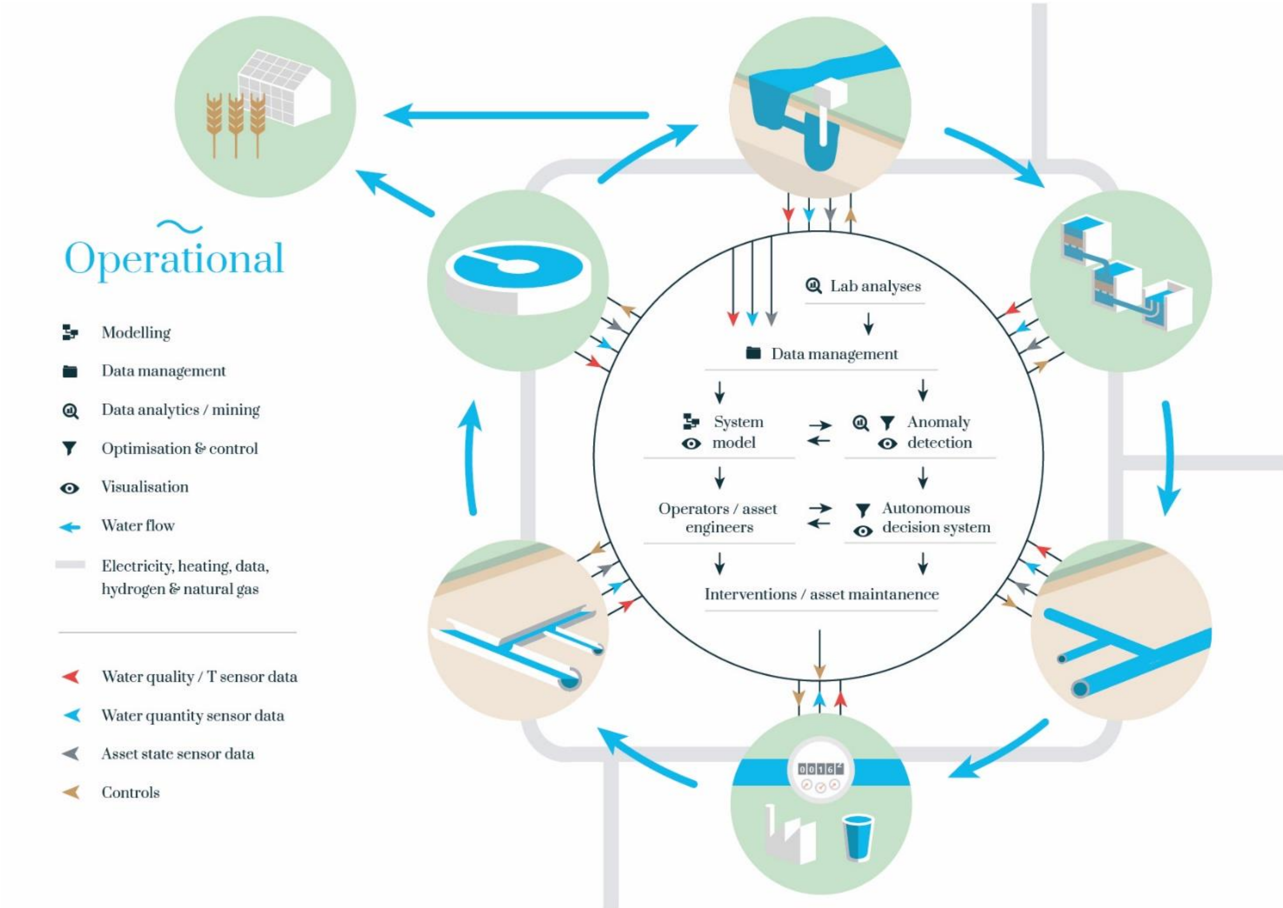

Figure III.1: Elaborate schematic representation of the vision of the role of HI and SW in the Dutch water sector and the interactions between domains at the operational level.

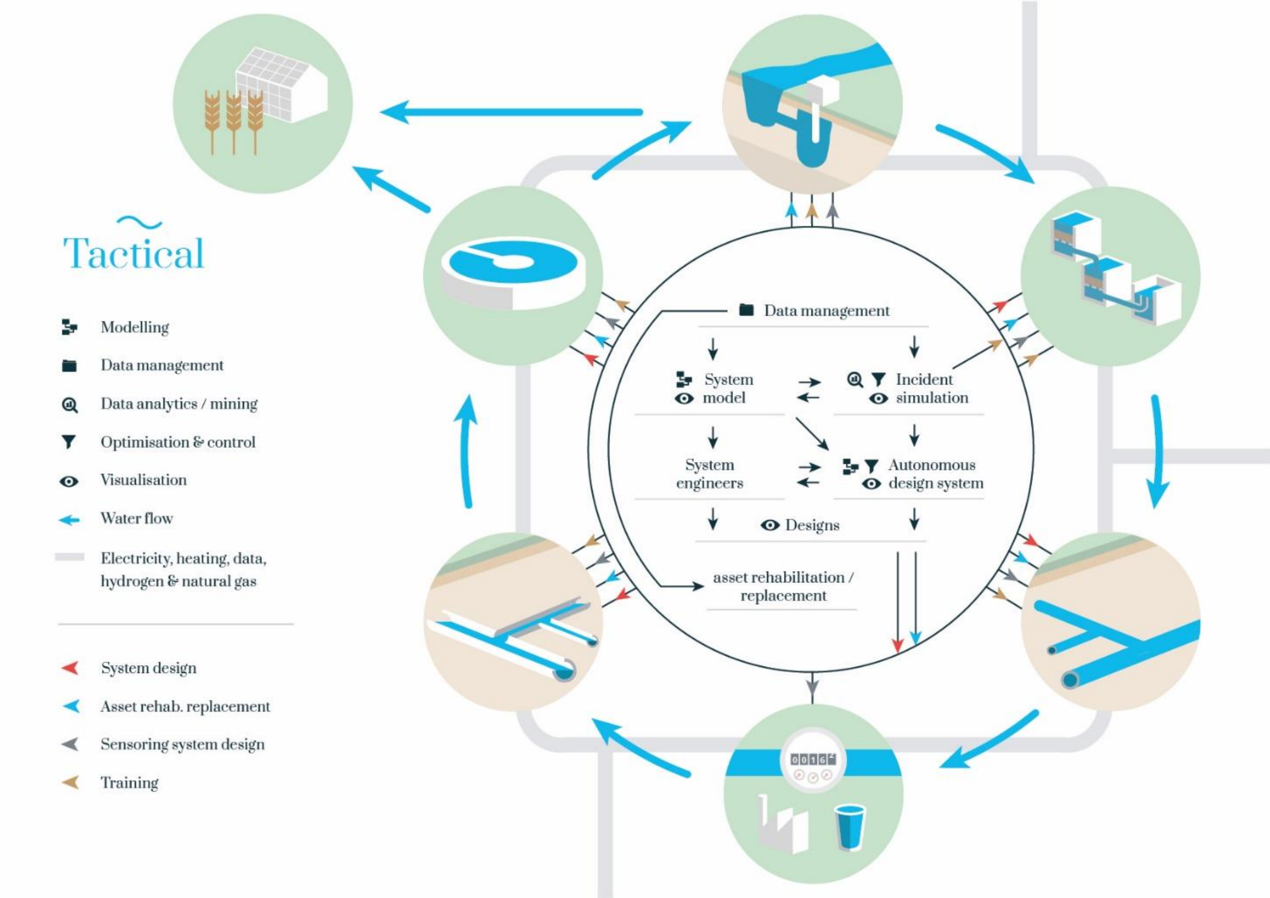

Figure III.2: Elaborate schematic representation of the vision of the role of HI and SW in the Dutch water sector and the interactions between domains at the tactical level.

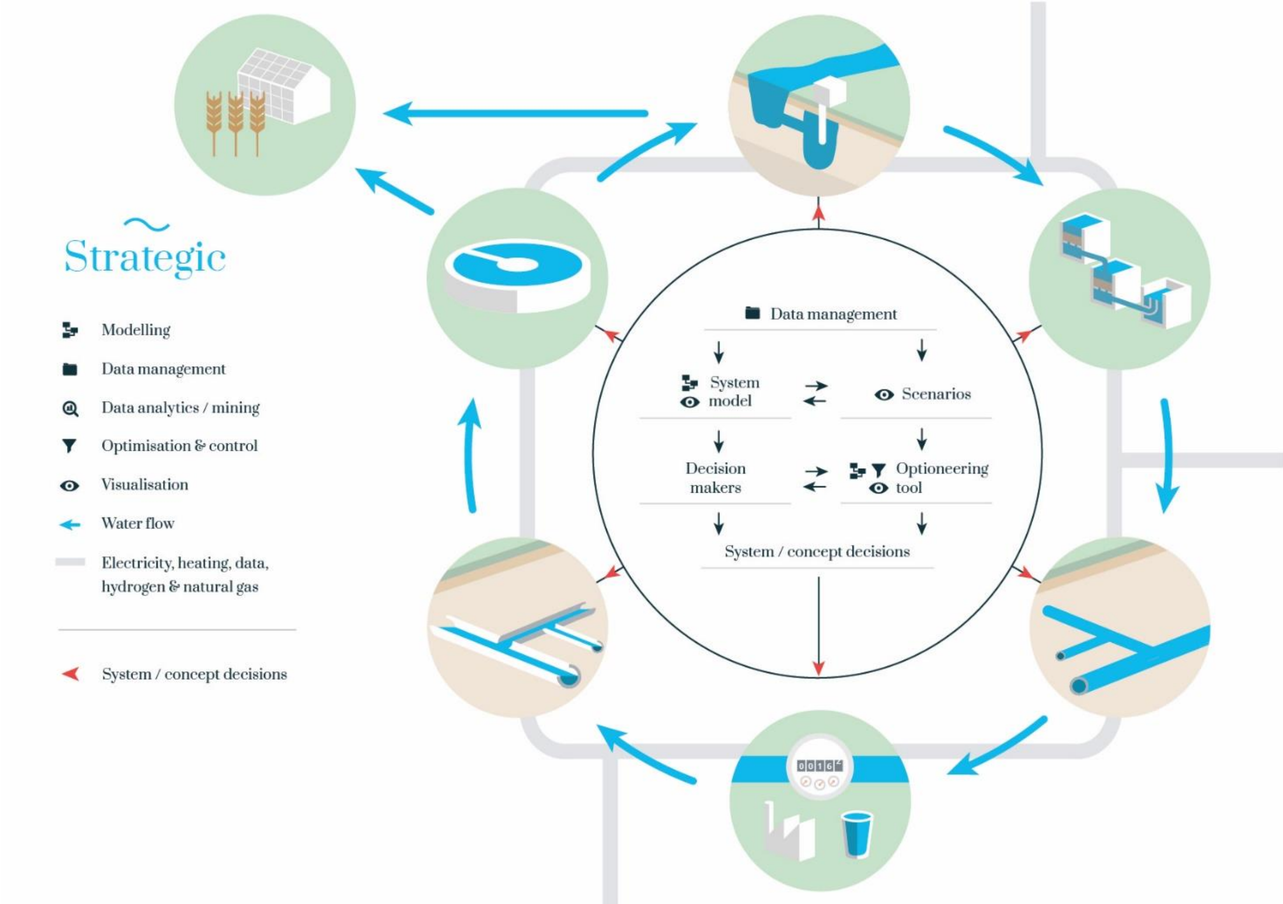

Figure III.3: Elaborate schematic representation of the vision of the role of HI and SW in the Dutch water sector and the interactions between domains at the strategic level.