The Future of Water A collection of essays on "disruptive" technologies that may transform the water sector in the next 10 years

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The future of Water

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TABLE OF CONTENTS

ABSTRACT

Innovation is quickly and inevitably changing the way we think and provide infrastructure services. Processes are being transformed and boundaries across sectors shifted. In the era of smart homes and phones, big data and satellite imagery, how will innovation impact the water sector by 2030? This volume compiles the answers to this question from four experts on the field. In each individual essay, experts identify what they believe to be the key technological changes that will transform the sector and whether they have the potential to become "disruptive". Attention is also paid to the context, as authors discuss which enabling conditions - e.g. regulation, policy, markets - would be necessary to encourage the adoption and mainstreaming of each technology.

FOREWORD

Innovation is quickly and inevitably changing the way we think and provide infrastructure services. In many sectors, technology is disrupting processes and market structures. The ability to harness solar power at home has the potential to turn consumers of electricity into providers, or “prosumers”. Solar-powered self-driving vehicles are blurring the boundaries between the energy and the transport sectors and is likely to significantly impact citizen mobility in the near future. In the water sector, however, despite the application of many of these new technologies, there are divergent views about the extent to which they have the potential to disrupt the sector.

The collection of essays in this volume exemplifies this variety of perspectives. In the first essay, Dr. Glenn Daigger (Professor of Engineering Practice, at the Department of Civil and Environmental Engineering of the University of Michigan and President and Founder of One Water Solutions, LLC) discusses the expected shift in urban water management and how emerging new challenges require rethinking the approach that was designed in the XIX and XX centuries. He foresees these large-scale and centralized water management systems giving way to more decentralized systems optimized to promote the reuse of water, including the recovery of resources and nutrients from the treatment processes. *The One Water* slogan encapsulates the idea of a future-proof water management approach that makes the most of water in all of its states (groundwater, rainwater, potable or used water) and serves multiple purposes adapted to local conditions.

The second essay by Dr. Upmanu Lall (Professor of Engineering at Columbia University and the Director of the Columbia Water Center) agrees that traditional and centralized Water and Wastewater systems are likely to be replaced by revolutionary decentralized networks that rely on remote sensing and digital technologies to control water quantity and quality parameters to ensure safe and affordable drinking water. Dr. Lall also discusses the challenges posed by the risks of floods and droughts, which lead to significant annual average losses globally, and are projected to increase in frequency and impact. He foresees an increase in creative financial instruments to address climate risks (e.g., index insurance, or catastrophe bonds). Lastly, he discusses how a well-developed set of principles for water resource management and regulation (even when present) cannot guarantee effective environmental management and regulation. A more integrated and coordinated action could be promoted by participatory, adaptive approaches for monitoring and investment in watershed services that address the cumulative effects of human use on water quantity and quality.

Nikolay Voutchkov, an internationally recognized desalination expert, President of Water Globe Consultants, LLC and Director of the International Desalination Association, defines "disruptive" as a solution that is at least 20% more efficient than the existing alternative. Based on this metric the author discusses a host of technological innovations and their expected impact on the sector. One key example of disruptive innovation in his view is the rapidly increasing efficiency, productivity and durability of membranes used in desalination. While considered by many a "niche solution", the author argues that by 2030 desalination could provide approximately 25% of the municipal water supply of the urban coastal centers worldwide (currently estimated 10%). He argues further that similar technical improvements are happening in the water reuse field. Rapidly decreasing production costs are making these sustainable options, a viable alternative to cheaper, but finite conventional freshwater resources, thus enabling water stressed areas to "diversify the portfolio of water supply".

Some promising innovative solutions discussed in this essay (and relative enabling conditions) are in the fields of Digital water, Water reuse, Resource recovery, and Desalination.

In the fourth essay, Will Sarni (Founder and CEO at Water Foundry, as well as a Former Deloitte Consulting Director) offers a deep dive into how digital technologies are progressively transforming the water sector by enabling real time water quantity and quality monitoring.

Taking a closer look at the ongoing digitization of the water sector, the author explores its potential to strengthen the watershed—assets—consumers value chain. For upstream surface and groundwater monitoring, satellite imagery is already extensively used, as well as for flood forecasting. Moving along the value chain, the author points out that the most forward-looking water suppliers have already started to use Advanced Metering Infrastructure (AMI) systems to gather, process and analyze real-time data on pressure, flow, and water quality. Thanks to the insights from these data, incidents like corroded pipes, leaks or even contaminations can now be remotely predicted and addressed with significant improvements in efficiency. What is more, the author states that exploiting "digital twins" (providing a complete virtual model mirroring physical assets) is opening up new possibilities also for simulating modifications to the water systems before they are implemented in reality. With software like Dropcounte and WaterSmart, digitization can also become the tool to engage the end consumers in sustainable behaviors making them aware of individual water consumption patterns.

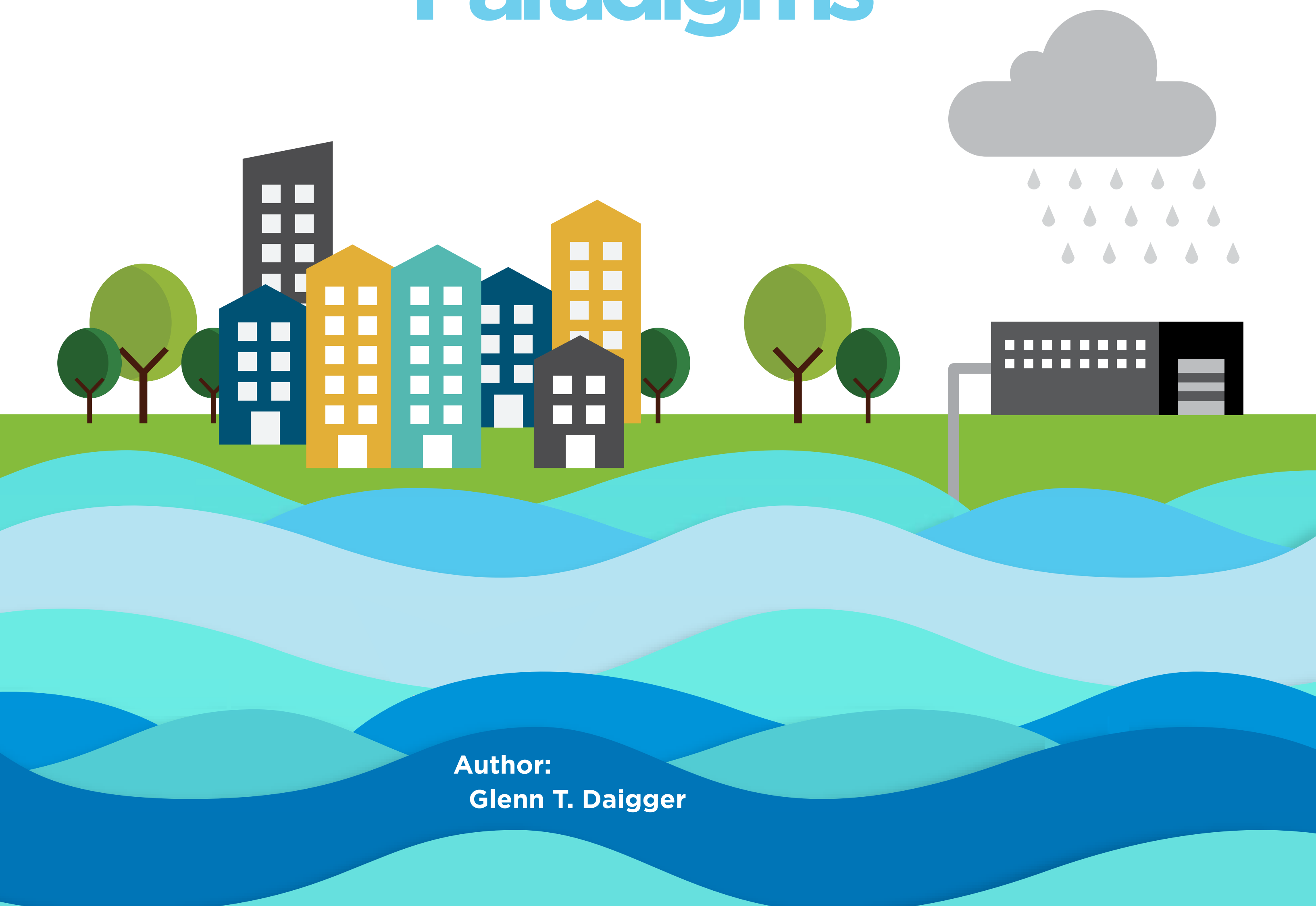
A clear, albeit somewhat counterintuitive, insight agreed upon by the experts is that technology, by itself, cannot bring radical change (let alone "disrupt" a pre-existing market solution). While, technology-wise, the water sector seems ready to shift towards a more responsible, sustainable and transparent "One Water" approach to water management, the essays raise critical questions about two important elements in this process.

The first is regulation. What are the necessary conditions for technological innovation to be widely adopted? Will the emerging technological advances push for the needed regulatory reforms, or is regulation reform a pre-requisite for the sector to seize the opportunities presented by innovation? Some familiar Silicon Valley stories (e.g. Uber or Airbnb) exemplify disruptive innovation happening prior to regulatory reform. As consistently pointed out in the papers, however, regulation plays a much more prominent role in a sector traditionally managed as a natural monopoly, and constrained by the recognition of water as a human right.

The second element is one of scale. What would be the optimal level at which to promote and adopt such changes? Many of the innovations aligned with the concept of One Water are local and can be applied at a smaller and decentralized scale. Most of the best practices showcased are found at the city level: Singapore's Public Utility Board (PUB) operates as a holistic smart water grid, while China aims to turn 16 flood-prone urban areas into "sponge cities" absorbing and reusing at least 70% of rainwater by 2020. In a generally water-rich region like Latin America and the Caribbean, certain cities especially hit by weather and water-related issues might have a stronger incentive to re-think their water management systems. Of course, whether municipal agencies have enough financial resources (or political will) to embark on the necessary retrofits and innovations remains a challenge.

We hope this collection of essays will provide some food for thought and inspire continuous dialogue on these critical questions.

I. One Water and Resource Recovery: Emerging Water and Sanitation Paradigms



Author:
Glenn T. Daigger

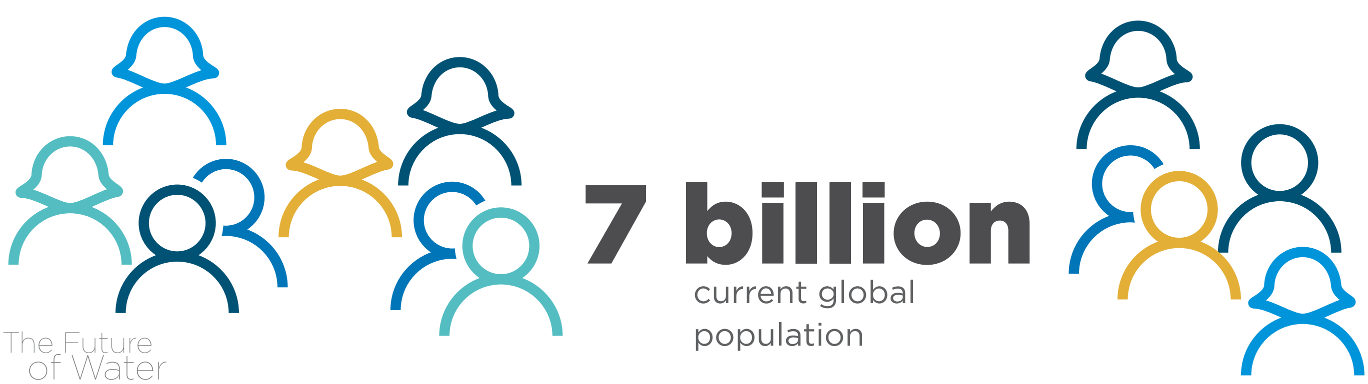
1.1 HISTORICAL PERSPECTIVE ON URBAN WATER MANAGEMENT DEVELOPMENT

The historical approach to urban water management (drinking water, rainwater, used water) has been "reinvented" many times over human history, most recently beginning in the industrialized cities of Europe and the United States (US) in the 19th and early 20th century (Schneider, 2011; Sedlak, 2014). The spread of waterborne disease (e.g. cholera, typhoid) in urban areas caused by pollution of local water supplies lead to importation of uncontaminated water from remote sources. While this largely addressed drinking water related public health issues, it created the "problem" of sewage resulting from significantly increased volumes of contaminated (used water). The issue of sewage was subsequently addressed, along with drainage and flooding issues, by transporting the contaminated water out of the urban area for remote discharge. Pollution problems caused by these discharges compromised the quality of some drinking water sources, leading to development of drinking water treatment, and environmental degradation caused by pollution discharges lead to the development of used water (often called wastewater by others) treatment. Due to economies of scale for construction of these large-scale conveyance systems, and the limited treatment technologies available at the time, these systems were implemented as large-scale centralized systems, consisting of extensive piping networks and a small number of relatively large treatment facilities. While this general approach remained the norm throughout the 20th century, changes are occurring in the 21st century as described below.

The large-scale and centralized nature of the current urban water management system generally minimizes capital investment for the supporting infrastructure through economies of scale for facility construction, but often at the expense of efficient resource use. The large-scale, centralized systems are relatively energy-intensive (compared to alternatives), and minimize opportunities for resource recovery. Transport of water (e.g. drinking, used, reclaimed fit-for-purpose water) is energy-intensive, and these energy costs can be minimized if water supplies are produced locally and used water is treated for reuse locally. Combining various components of the used water stream for joint transport reduces resource recovery opportunities, as discussed below. While many factors were responsible for adoption of this approach during the 19th to early 20th century, two of the most important were the general availability of water and other resources, relative to demand, and the general lack of treatment technologies.

During the time that our current approach developed the global population was growing from 1 billion at the beginning of the 19th century to 2 billion in the first quarter of the 20th century (Wikipedia, 2018), compared to the current global population of over 7 billion (UN, 2017). Economic growth, which is the true determinant of water demand, has grown much faster. Moreover, the urban population has grown from around 20 to more than 50 percent of the total (UN, 2018). Thus, while water and other resources were generally available in the 19th and early 20th century, this is no longer the case. Today, available sustainable water resources are generally fully allocated, and in many regions of the world are over-allocated (UN, 2012). In fact, the growing water stress experienced throughout the world may be considered a result of the water management systems historically adopted.

Secondly, the general lack of technologies to reliably and cost-effectively treat contaminated water lead to the need to source relatively uncontaminated water supplies remotely, and to convey contaminated water for remote disposal. In contrast, treatment technologies are now available to treat relatively contaminated water to potable, and even higher, quality standards. Thus, the factors that principally resulted in development of the current urban water management system no longer exist.



1.2 DEVELOPMENT OF ONE WATER AND RESOURCE RECOVERY SYSTEMS

Today we face increased resource scarcity (water and other resources), compared to the 19th and early 20th century when the current urban water management system evolved (Steffen, *et al.*, 2015; Hoekstra and Wiedmann, 2014; Rockström, *et al.*, 2009). Water resource scarcity is further exacerbated by climate change, which is decreasing available sustainable fresh water resources. Thus, it becomes necessary to implement systems that use available fresh water and other resources more efficiently. Fortunately, such systems exist and are being increasingly implemented (Wang, *et al.*, 2018; Larsen *et al.*, 2016; Hering, *et al.*, 2013; Daigger, 2012a, 2010, 2009, 2007). Table 1 contrasts some of the essential features of the historic approach to urban water management with the systems evolving to meet current and future needs. The evolving systems are integrated, multipurpose in nature, and rely much more heavily on local as compared to remote water supplies. These systems incorporate both centralized and distributed system components (often referred to as hybrid systems), and optimize operational features such as water use, energy, materials, and operational labor, rather than simply minimizing infrastructure cost. These systems are much more integrated into the urban systems that they are a major component of, thereby requiring significant institutional and financial changes (IWA, 2016a). They are also increasing integrated into the evolving circular economy (IWA, 2016b). While the "Future" scenario described in Table 1 certainly does not yet represent the norm, leading cities around the world are increasingly adopting these system components. As a result important examples existing internationally.

Table 1. Comparison of Historic and Future Approach to Urban Water Management

Item	Historic (19th and Early 20th Century)	Future (21st Century)
Relationship to Economy	Provide Cost-Effective Water Service	Integral Part of Circular Economy
Functional Objective	Comply with Regulations	Produce Useful Products
Optimization Function	Infrastructure Cost	Water Use, Energy, Materials, Labor
Water Supply	Remote	Local
System Components	Separate Drinking Water, Rainwater, and Used Water Systems	Integrated, Multipurpose Systems
System Configuration	Centralized Treatment	Hybrid (Centralized and Distributed) Systems
Financing	Volume Based	Service Based
Institutions	Single Purpose Utilities	Integrated, Water Cycle Utilities
System Planning	"Plumb up" the Planned City	Integrated with City Planning

Source: author's own creation

Important components of the emerging paradigm are referred to as "One Water" and "Resource Recovery" and are deployed as components of integrated urban water management systems.

I.2.1 One Water

One important component of the evolving approach to urban water management can be referred to by many names, but one frequently used (and the favorite of the author) is "One Water". One Water is based on the concept that all forms of water in the urban area (rainwater, groundwater, surface water, drinking water, used water) are linked and form a system that is best managed in an integrated fashion to provide effective urban water service. It is further recognized that the urban water cycle is connected to the broader environment, especially including the watershed where the urban area is located. To provide effective service the system must address the extreme conditions of drought and flooding (e.g. "too little" and "too much" water). The One Water approach addresses these conditions using a portfolio approach consisting of a combination of options, each one performing well over different conditions so that the combined system is resilient over a wide range of conditions. The portfolio components relative to water supply include surface and ground water, conservation, rainwater harvesting, water reclamation and reuse, and (as a last resort) brackish and sea water desalination (NAE 2016, 2012). Likewise, the portfolio components relative to excessive water (storms, potentially leading to flooding) consist of conventional stormwater systems (including storage, piped conveyance, and physical flood protection, e.g. dikes), natural systems which capture and infiltrate water (green infrastructure), and designing the urban form to provide locations such as parks, etc. which can flood and be returned to service quickly and with minimal damage. In all cases the system components, and their relative sizes, are determined by local conditions.

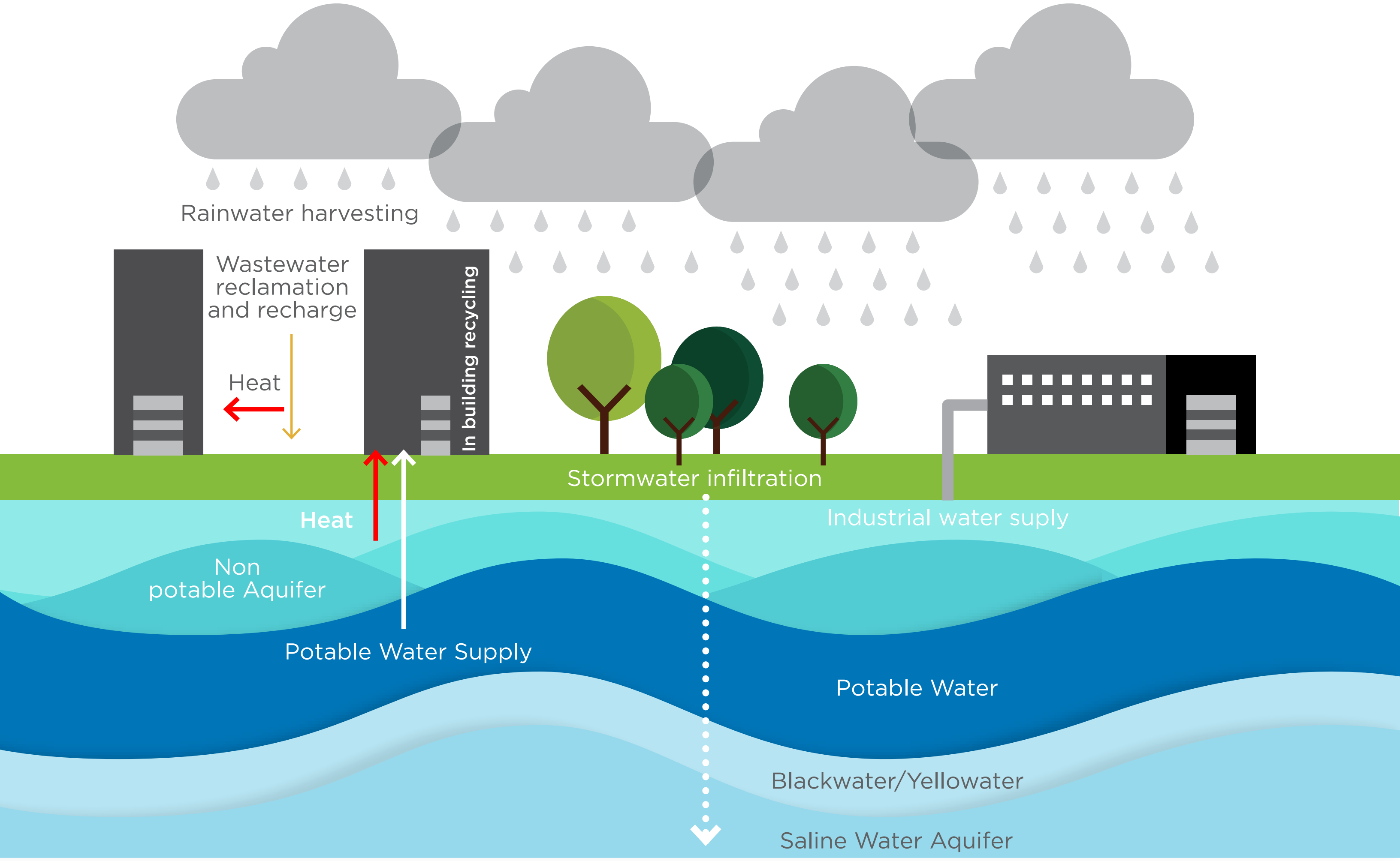
I.2.2 Resource Recovery

The One Water approach is leading to urban water management systems using existing water supplies much more efficiently through conservation, rainwater harvesting, and reclamation and reuse. Other resources present in the urban water cycle can also be harvested, including energy, nutrients and other materials (IWA, 2016c; Daigger, 2012a, 2009). Forms of energy include kinetic (the energy of flowing water), thermal, and chemical (such as the organic matter present in used water). We are all familiar with use of flowing water to generate electricity through hydropower systems. Thermal energy can be recovered from, or discharged to, water using existing heat exchange technology, including heat pumps. Organic matter can be captured from used water in the form of sludge produced through used water treatment and converted into biogas through anaerobic processes. Biogas can subsequently be used for a variety of purposes, such as in combined heat and power (CHP) systems, or upgraded to natural gas quality. Nutrients are recovered when biosolids products are produced for in agricultural use, and phosphorus is already being recovered as the slow release fertilizer product struvite (magnesium ammonium phosphate). Approaches to harvest other forms of carbon, nitrogen, and rare earth metals are also being investigated. Recovery and use of these resources can provide financial and strategic advantages to urban water utilities, along with broader life cycle advantages due to reduced need to extract these resources from the environment. Financial advantages result, both from the revenue generated by the recovered resources, but also because of the costs avoided in used water processing (such as reduced scaling in anaerobic digestion systems when struvite is recovered). Strategic advantages arise when desirable products are produced, rather than residuals (sludge) that are not perceived as useful to society. The result is increased public acceptance for the processing and management of these materials, rather than disposal.

I.2.3 Integrated Systems

The individual components of One Water and Resource Recovery systems are then combined into an integrated system that meets the needs of individual urban areas. As compared to the historic approach, forward-looking systems increasingly incorporate distributed components (Siegrist, 2016), along with traditional centralized systems. This arises because more recently developed treatment technologies (addressed below) allow source waters of various qualities (surface, ground, rain, and used) to be treated to meet the quality requirements for various uses – the concept of "fit for purpose" (as opposed to treating all water to potable quality) water production and use. While the "fit for purpose" concept is compatible with a fully centralized system, it becomes even more economical with a hybrid centralized and distributed system. Water production facilities can be located close to local water sources and areas of demand. For example, used water can be diverted out of the collection system and treated to a quality level appropriate for particular uses, such as irrigation, cooling, and domestic non-potable. Residuals from treatment can be returned to the collection system and conveyed to a larger, centralized treatment facility where recovery of energy and nutrients can be accomplished economically at the larger scale of such facilities. Source separation (separately collecting grey, black, and yellowater) is also an emerging trend which can provide inherent benefits from both resource efficiency and recovery perspectives (Daigger, 2012b).

Figure 1 provides an illustration of such an integrated system incorporating centralized and distributed components. Both potable and non-potable water supplies are provided to municipal, commercial, and industrial customers. This example illustrates these water supplies being provided by local non-



Source: based on author's own creation

Figure 1. **Example Integrated One Water/Resource Recovery Hybrid Centralized and Distributed Urban Water Management System.**

potable and potable water aquifers. Water supplies are supplemented, either directly or by supplementing the non-potable aquifer, by rainwater harvesting, stormwater infiltration, and wastewater reclamation (largely from greywater). Blackwater and yellowater are collected separately for resource recovery. Heat is recovered from the used water stream and the non-potable aquifer. Salts added through water use are concentrated into a saline water stream that is exported to a saline water aquifer. While not all components incorporated in this illustration will be included in all systems, the concept is illustrated.

1.3 ENABLING TECHNOLOGIES AND PRACTICES

New technologies and improved practices continue to develop and enable the integrated systems described above. While further technological advances are occurring and expected, Table 2 lists existing, well-developed technologies and practices that are currently enabling the systems described above. Technologies such as advanced oxidation, membranes, and ultraviolet (UV) treatment can be applied at various scales and with various water sources (ground, surface, rain, and used water) to produce product water meeting a wide range of fit-for-purpose quality requirements (Zodrow, *et al*., 2017). The modular nature, performance resilience, and ability to remotely monitor performance allows these technologies to be applied at a wide range of scales, from small distributed to large centralized applications. Membranes can be coupled with biological treatment systems when treating waters containing biodegradable organics, forming the membrane bioreactor (MBR) and anaerobic membrane bioreactor (AnMBR) processes (Judd and Judd, 2011). Anaerobic systems can also be applied to a wide variety of water types and scales (distributed to centralized) to remove biodegradable organics with minimal energy input and recover the embedded chemical energy by conversion to biogas. Thermal hydrolysis (THP) is used in larger-scale centralized systems to pre-treat organic material prior to anaerobic treatment, thereby increasing biogas yield and reducing anaerobic treatment system size. Struvite precipitation can be applied at local (distributed) or centralized scales to recover phosphorus through conversion to fertilizer

Source separation and fecal sludge management are alternatives to the traditional approach. Greywater is relatively uncontaminated (compared to blackwater and yellowater), and often represents the largest used water volume. Separate collection of greywater results in a water supply that requires less treatment than the combined used water stream, thereby allowing use of less energy- and chemical-intensive treatment systems to produce fit-for-purpose water supplies. Implementing this approach using many small-scale, distributed collection and treatment systems minimizes piping to collect the separated greywater and distribute the product water produced by appropriate treatment systems. Yellowater represents less than 1 percent of the combined used water volume but contains about 60 percent of the phosphorus and nearly 80 percent of the nitrogen. Diversion of this small volume, high nutrient concentration stream simplifies treatment of the remaining used water, and allows for increased capture of the nutrients it contains for reuse. Blackwater contains much of the organic matter but in a smaller volume, making anaerobic treatment for biogas production more efficient. Fecal sludge management represents application of these concepts in locations where traditional water supply and used water collection are not provided (Strande, *et al*., 2014). Fecal matter, either with or without urine, is collected and periodically transported to a centralized location for processing to recover energy and nutrients in a manner which is protective of public health and the environment. Separate collection of fecal matter and urine further enables resource recovery.

1.4 IMPLEMENTATION STATUS

The system components, technologies, and approaches described above are in various stages of development and application, but most have a significant number of full-scale applications in numerous settings. Advanced oxidation, membrane systems, and UV technologies are now widely applied in a variety of applications. Advanced oxidation is increasingly applied in advanced water treatment and water reuse applications, and it is receiving increased consideration for the control of micro-constituents (e.g. pharmaceuticals, hormones) in used water discharges. Membrane systems (micro-filtration, untra-filtration, nanofiltration, and reverse osmosis) have become standard technologies, applied in a wide range of treatment applications, and aerobic MBR's have become a standard biological treatment technology, especially for water reuse applications. Anaerobic systems are widely used in industrial treatment applications and is a standard technology for the stabilization of the organic sludges produced in used water treatment. Interest in anaerobic systems for direct treatment of used water continues to grow. THP is increasingly used to pre-treat organic sludges produced in used water treatment prior to anaerobic treatment. A number of specific technologies to recovery phosphorus by struvite precipitation are available, and the number of installations is increasing rapidly.

Distributed system components are increasingly being added to existing centralized systems to increase capacity, improve level of service, increase resilience to the impacts of climate change, improve resource use efficiency, and improve resource recovery. Distributed rainwater capture and natural rainwater treatment systems which infiltrate captured water into local aquifers add to local water supplies and mitigate flooding and pollution caused by uncontrolled run-off. A significant number of applications already exist, and further applications are progressing on a global basis. These systems provide further value to their subject urban areas, for example by improved recreation and aesthetics along with reduced heat island effect. Water reclamation and reuse facilities provide a drought-resistant water supply while reducing pollution discharges. Locating such facilities adjacent to fit-for-purpose water demands that can be met with available quantities of used water reduces used and reclaimed water conveyance requirements. The concept of "sewer mining", i.e. locating a water reclamation facility to meet local fit-for-purpose water supplies, is a well-established practice in several locations, including the arid Southwestern U.S. and Australia. Adding distributed system components in this fashion can supplement existing centralized systems and allow them to serve increasingly dense urban areas without the disruption associated with expanding the centralized system water distribution and used water collection system. Source separation can be incorporated into new construction and as existing buildings are renovated.

Separate greywater collection and treatment for reuse has been applied in such diverse locations as China (Qingdao) and California (San Francisco). Full-scale examples of urine diversion are just beginning to appear, but include examples in the U.S. and Europe (i.e. Paris).

Peri-urban areas can be served by distributed systems when a centralized system is either not present, or it is not cost-effective to extend the centralized system to the newly developing area. Fecal sludge management approaches can provide effective sanitation, resulting in the protection of public health and the environment. This approach is particularly applicable in locations such as informal settlements where conventional water supply may not be available, but is also certainly applicable when greywater is separately collected and managed as a local water supply. Examples are emerging rapidly, for example in sub-Saharan Africa. Combining distributed and centralized system components allows for phased upgrade and expansion of the urban water system as demand and the desired level of service increases. The success of these hybrid centralized and distributed systems is resulting in greatly expanded implementation. These systems are expected to become the norm over the next decade or two.

15 to 20

years is generally required for new technologies to become material in the water sector

1.5 FURTHER DEVELOPMENTS

While new technologies will continue to develop, current technology is sufficient for the continued implementation of the One Water and Resource Recovery focused hybrid centralized and distributed approaches described above. A period of 15 to 20 years is generally required for new technologies to become material in the water sector (O'Callahan, *et al.*, 2018), and significant changes in practices require even longer. Thus, it is unlikely that newly developing technologies will become material over the next 10 to 15 years, say by 2030. Technologies currently being translated into practice are generally consistent with the overall approach described above and, consequently, are unlikely to change the general direction of change and, most likely, will accelerate it. One trend that is expected to become material within this timeframe is the broader application of sensors, coupled with "big data" approaches to manage and optimize the use of both centralized and distributed infrastructure. Already a trend, these developments will serve to enable and accelerate implementation of these more complex and integrated, but higher performing, systems. Improved monitoring and analysis will also result in increased insights relative to superior approaches for integrating system components, leading to further improvements. These advances, coupled with the general learning resulting from the increasingly widespread application of these approaches, will further accelerate their evolutions and rate of adoption.

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ANNEX

A list of emerging technologies.

Table 2. Technologies and Practices Transforming Urban Water Management		
Technology	**Description**	**Application**
Advanced Oxidation	Application of a combination of oxidants, such as ozone or hydrogen peroxide and UV, which produce high reactive oxygen species	Oxidation of recalcitrant organic compounds, either fully to CO_2 and H_2O, or partially to increase biodegradability to allow metabolism in downstream process, often biologically activated carbon (BAC)
Anaerobic Treatment	Biological processes excluding oxygen and nitrate as terminal electron acceptors to convert biodegradable organic matter in biogas (methane and CO_2)	Widely used historically for treatment of sludges produced in used water treatment, a wide range of processes are available and continue to be developed to treat lower-strength wastewaters of various types.
Fecal Sludge Management	Low-water sanitation where fecal matter (and also potentially urine) is collected in a semi-solid form and transported for treatment and reuse	Provides for proper management of feces and urine in areas where conventional wastewater collection systems are not present
Membranes	Polymeric (usually) membranes of various configurations able to separate particles (micro- and ultra-filtration) or dissolved substances (reverse osmosis and nano-filtration) from water	Wide variety of applications, ranging from quite small-scale to large centralized systems. Can also be coupled with and provide the necessary liquid-solids separation for biological systems, such as membrane bioreactors
Source Separation	Conventional used water is actually formed by combining greywater, blackwater, and yellowater at the household scale. In source separation approaches the separation is maintained and these individual streams are collected and conveyed to treatment separately	A historical practice which is re-emerging in a variety of contexts. Greywater is relatively uncontaminated and can be efficiently treated for fit-for-purpose use while blackwater contains most of the chemical energy (organic matter) and yellowater the nutrients. Facilitates resource recovery and use
Struvite Precipitation	Precipitation of phosphorus and ammonia as $MgNH_4PO_4 \cdot 6\,H_2O$ (struvite)	Struvite is a slow release fertilizer that can be recovered from used water streams
Thermal Hydrolysis (THP)	Steam explosion of organic matter to convert particulate and colloidal organic matter into dissolved form	Subject conversion increases the rate and extent of biodegradation of organic matter, particularly prior to anaerobic treatment
Ultraviolet (UV)	The application of particular wavelengths (e.g. 254 nm) of light to water to inactivate pathogens and/or as a component of an advanced oxidation system	Easily applied at a wide variety of scales for fit-for-purpose water production.

Source: author's own creation

II. Disruptive Innovations in the Water Sector

Author:
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II.1 INTRODUCTION

The water industry today faces multiple challenges – from accelerated population growth, to exhaustion of our traditional water sources, and water scarcity driven by climate change and inefficient management of our available water resources. According to a recent United Nations report, almost half of the world's population — some 3.6 billion people — currently live in areas vulnerable to water scarcity and nearly 2 billion people could suffer water shortages by 2025. In response to these challenges, the water supply planning paradigm in the next 10 to 15 years will evolve from reliance on traditional fresh water resources towards building an environmentally sustainable diversified water portfolio where low-cost, conventional water sources (e.g., rivers, lakes and dams) are balanced with more costly but also more reliable and sustainable water supply alternatives such as water reuse and desalination.

Nature teaches us that sustainable existence of closed systems such as our planet has to rely on efficient circular path of use of resources such as energy and water – so the key lesson learned from nature is that circular economy is the only path forward towards sustainable economic growth worldwide. Water leaders have the responsibility to transform water from one-time resource to a renewable precious commodity, and to incorporate this commodity into a robust circular economy.

Circular economy and rational, responsible, renewable and sustainable use of water resources are closely intertwined. Looking beyond the current take-make-dispose extractive industrial model, circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling of economic activity from the consumption of finite resources, and designing waste out of the system. Underpinned by a transition to renewable energy sources and water reuse, the circular model builds economic, ecological, and social capital.

Experience to date has demonstrated that in order to incorporate seamlessly sustainable water management into circular economy we have to apply next-generation water management tools and water service models based on a combination of technological and non-technological solutions. In the next 15 years the water industry focus will be on closing the water loop and using alternative water resources, while decreasing energy consumption and closing material cycles where possible by extraction of energy and valuable compounds as much as possible. The tools of creating a sustainable one-water management and incorporating water management into circular economy by year 2030 are: digital water; water reuse; resource recovery and desalination. A number of disruptive technologies that are expected to accelerate the process of water utility transformation towards sustainability are presented below. These technologies are expected to result in exponential acceleration of the utility transition process towards sustainability by disrupting the status quo. In order for a technology to be disruptive it has to be: (1) unique and (2) significantly (at least 20%) more efficient than the existing technologies it replaces.

II.2 DIGITAL WATER

One of the key future trends of the water industry is in digitalization and the conversion of data into actionable insights. Digital water provides water management solutions that leverage the power of real-time data collection, cloud computing and big data analytics to minimize water losses in the distribution system and maximize operational efficiency, and asset utilization. The digital water management approach provides an integrated platform, which includes water production and supply asset management, water management software, intelligent controls, and professional expertize to drive down operating costs and water losses.

Digital water is transforming the way cities will use and manage water resources in the future. By 2025, about 80% of utilities in large cities of advanced countries and half of the utilities in large cities of developing countries are expected to have water supply systems incorporating Digital Water features such as advanced metering infrastructure (McKinsey & Company, 2018).

II.2.1 New and Emerging Technologies

Advanced Metering Infrastructure (AMI) Systems

AMI systems are computerized systems, which gather, process and analyze real time data of the water use in a given area serviced by the water utility. Water flow data from the customers and key points of the distribution system are collected on an hourly basis and are used not only for automated customer billing and fee collection but also for identifying locations which experience leakages and for quantifying and ultimately eliminating water losses expeditiously. Such systems have a key advantage that they can detect leaks before they burst and significant loss of water and disruption of water supply occur. These systems automatically generate work orders to address the identified operational challenges (leaks, malfunctioning equipment and instrumentation). With sensors becoming smaller and cheaper, utilities can deploy and link them into a smart water monitoring grid that requires minimal human intervention. Data analytics can help make sense of the vast amount of data from these sensors.

AMI systems are widely adopted by forward-looking utilities. For example, the Public Utility Board of Singapore (PUB) manages the entire water network as a system, including its design, operation and maintenance for 24/7 water delivery (PUB, 2016). PUB has developed a comprehensive smart water grid with three main objectives: asset management, promoting water conservation and providing good customer service. The grid uses more than 300 wireless sensors in the water mains to collect data on real-time pressure, flow, and water quality. Risk assessment and predictive software tools help identify the top 2% of high-risk pipelines for replacement annually. An online leak detection system monitors critical large mains for leaks, locates them to within 10-meter accuracy and alerts operators within 24 hours of the leak occurrence. Moreover, an automated meter reading system monitors and collects domestic water consumption data continuously, while home water management systems inform residents about their usage patterns and alert them to possible leaks and over-consumption. PUB also remotely monitors the water consumption of Singapore's top 600 commercial and industrial customers, and plans to develop water efficiency benchmarks and good practice guidelines for different sectors. In addition, PUB is planning to deploy sensors for quicker and more accurate detection of contaminants, better data analytics to filter out false alerts, and batteries to match the smart meters' 15-year lifespan.

Another example of AMI implementation is the Macao Water Supply Utility which has implemented an oversight system called Aquadvanced, which monitors consumption data collected from Macao's water network and alerts customers and operators to abnormalities (Suez, 2017). The system is easy to navigate and facilitates follow-ups after an abnormal event. For example, numerous staff might trace the reason behind an unusually high flow rate, but their different clearance levels mean only certain users have the authority to confirm and/or close events. User profiles are divided in the system for greater management and organization.

In Malta, the Water Services Corporation (WSC) has recently installed an automated meter management system, using technology from SUEZ Smart Solutions, to improve its network performance (Suez, 2011). With the system, WSC can keep an eye on the water network, carry out more efficient and preemptive maintenance, warn customers early about possible leaks, improve its analysis of water consumption patterns, and reduce water theft. WSC also plans to develop reports and software to analyze data from smart meters.

Satellite Monitoring Systems of Water Distribution Systems and Catchments

An alternative trend to AMI systems emerging in recent years is the use of satellites in outer space to monitor leaks in water distribution systems and environmental health of river catchments. Two leading companies offering such technologies – Utilis and Satelytics – have developed software that analyzes satellite images to detect leaks in the distribution system and identify areas in the river catchment that experience environmental challenges (Utilis, 2018; TechOhio, 2017). The satellite emits electromagnetic waves, which penetrate the earth and are reflected by electrically conductive media such as wet ground and create image that identifies locations where pipe leakage is identified. The satellite image is analyzed and web-based map is generated identifying the location of leaks.

Leaks as small as 0.1 L/min could be pinpointed by the satellite monitoring system and single image can cover area of 3,500 m^2. Utilis offers such satellite monitoring service on a monthly and bi-annual basis and has already been adopted by utilities in the UK, Germany, Romania and South Africa. While at present, the use of satellite images for leak detection is relatively costly (US$160/mile per year), it is expected that in the next ten years, the price to task a satellite to collect specific information from outer space is expected to diminish significantly and to make this technology more affordable and easy to use. However, even at present the cost of this leak the savings from lost revenue due to water leaks can offset detection service.

The US-based company, Satelytics uses geospatial image analysis from satellites, nanosatellites, drones and planes to monitor water quality in watersheds. The company monitors the health of vegetation sites using bi-monthly satellite image analysis and identifies whether the vegetation has been damaged or negatively impacted as well as where are the potential "hot spots" of pollutants such as phosphorus or nitrogen that could trigger algal bloom and damage the ecosystem.

In Singapore, the national water agency - PUB - uses robotic swans to complement its online monitoring system for large-scale watershed management. The swans monitor different physical and biological parameters in Singapore's freshwater reservoirs to provide real-time water quality information more quickly. This allows PUB to react to cases of outbreak or contamination more swiftly, compared to the previous time-consuming approach of using manpower to collect samples. To manage storm water, PUB also uses CCTVs and image analytics to monitor silt discharges at construction sites. It also correlates information from water-level sensors and flow meters to provide timely alerts and support drainage operation and planning needs.

II.2.2 Enabling Conditions for Digital Water

In order for digital water to become reality, the water utilities have to complete digitization of their water supply systems (pipe networks) and deploy sensors in the field to monitor the pressure, flow and water quality in key points of the water distribution system. The game changing technologies in the water sector in the next 10 to 15 years will be these that allow real-time water quality monitoring and predict and prevent water quality challenges before they occur. The future emphasis should be not as much on enhancing utilities ability to generate and process data collected online as much as on the implementation of analytical tools and software that swiftly identify leaks and other water losses and provide information needed for planned preventive and predictive maintenance.

At present, the main point at which the potable water quality is measured online and continuously monitored is the point at which this water leaves the drinking water plant. Deployment of such water quality monitoring technology in the distribution system and real-time tracking of changes in water quality for such key parameters as content of pathogens, disinfectants and corrosion indicators is expected to transform the digital water industry in the future.

One of the key challenges of embracing the word of digital water by utilities worldwide is the lack of standardization between various data collection, storage and monitoring digital platforms, equipment and instrumentation. Therefore, the water industry is working towards the development of international standard for hardware and software platforms that allow to seamlessly integrate data generated from sensors of a number of sensor providers. In order to achieve interoperable solutions, the water industry needs the creation of smart water platforms with hybrid architectures that enable integration of data, services and, billing and work order processing software as well as a catalogue of best practices for data management and use. At present the efforts on the standardization of various digital platforms available on the market place is in its infancy and it is likely that such standardization would take at least 10 years to complete. At this time, these is a big gap of the level of adoption of digital water in developed and developing countries, which is mainly limited by resources and availability of sophisticated workforce needed to operate and maintain the digital water platforms and associated field equipment and instrumentation.

II.3 WATER REUSE

Water Reuse is becoming a cornerstone of sustainable water management and urban planning and a key chain-link of circular economy. Advances in science and technology greatly contributed to the implementation of new more efficient and reliable wastewater treatment. Producing reclaimed water of a specified quality to fulfill multiple water use objectives is now a reality due to the progressive evolution of water reclamation technologies, regulations, and environmental and health risk protection. Today, technically proven water reclamation and purification technologies are producing pure water of almost any quality desired including purified water of quality equal to or higher than drinking water.

The critical analysis of the state-of-the-art of water reuse confirms that the beneficial use of recycled water is a global trend with sustainable growth worldwide. Technology is playing a critical role as an enabler of water reuse and diversification of water reuse practices. Growing concerns of water scarcity, climate change impacts and promotion of circular economy are becoming major drivers for the increasing use of recycled water for non-potable application (e.g., agricultural irrigation and cooling water for power production) as well as for indirect and direct potable reuse.

Water reuse practices can be classified into two main categories: non-potable and potable water reuse. The most important characteristics, key issues and lessons learned for alternative water reuse practices are summarized in Table 1. The most common applications of non-potable reuse of recycled water include: agricultural irrigation, landscape irrigation, industrial reuse and groundwater recharge (Lazarova, 2012).

Table 1
Categories of Municipal Wastewater Reuse Applications and Related Issues or Constraints

Category			Potential application	Issues/constraints	Lessons learned
Non potable water use	Agricultural irrigation	Unrestricted or restricted	Food crop eaten raw Food crop processed or cooked Pastures for milk production Orchards, vineyards with or without contact with edible fruits Fodder and industrial crops Ornamental plant nurseries	Water quality impacts on soils, crops, and groundwater Runoff and aerosol control Health concerns Farmers acceptance and marketing of crops Storage requirements	Good practices available to mitigate adverse health and agronomic impacts (salinity and sodicity) Storage design and irrigation technique are important elements Numerous reported benefits
	Landscape irrigation		Golf courses and landscape Public parks, school yards, playgrounds, private gardens Roadway medians, roadside plantings, greenbelts, cemeteries	Water quality impacts on ornamental plants Runoff and aerosol control Health concerns Public acceptance Water quality control in distribution systems	Successful long-term experience Good agronomic practices On-line water quality control can ensure health safety Numerous benefits

Table 1
Categories of Municipal Wastewater Reuse Applications and Related Issues or Constraints

	Category		Potential application	Issues/ constraints	Lessons learned
Non potable water use	Urban uses		In-building recycling for toilet flushing Landscaping (see irrigation) Air conditioning, Fire protection Commercial car/ trucks washing Sewer flushing Driveway and tennis court washdown Snow melting	Health concerns Control of water quality and biological growth in distribution systems Cross-connection control with potable water Cost of distribution systems	Dual distribution systems require efficient maintenance and cross-connection control No health problems reported even in the case of cross-connections (for tertiary disinfected reclaimed water)
Non potable water use	Environmental/ Recreation uses	Unrestricted or restricted	Recreational impoundments Environmental enhancement (freshwater or seawater protection) Wetlands restoration Fisheries Artificial lakes and ponds Snowmaking	Health concerns Eutrophication (algae growth) due to nutrients Toxicity to aquatic life	Emerging application with numerous benefits for the cities of the future: improving living environment, human wellbeing, biodiversity, etc. On-line water quality control can ensure health safety
Non potable water use	Industrial reuse		Cooling water Boiler feed water Process water Heavy construction (dust control, concrete curing, fill compaction, and clean-up)	Scaling, corrosion and fouling Biological growth Cooling tower aerosols Blowdown disposal	Water quality to be adapted to the specific requirements of each industry/ process Request for high reliability of operation, cost and energy efficiency

Table 1
Categories of Municipal Wastewater Reuse Applications and Related Issues or Constraints

Category			Potential application	Issues/ constraints	Lessons learned
Potable water reuse	Indirect potable reuse with replenishment of: Reservoirs	Aquifers	Groundwater replenishment by means of infiltration basins or direct recharge by injection wells Barrier against brackish or seawater intrusion (direct recharge) Ground subsidence control	Health concerns Groundwater contamination Toxicological effects of organic chemicals Salt and mineral build-up Public acceptance	Successful practice since 1970s Multiple barrier treatment ensures safe potable water production Efficient control by means of advanced modelling tools
		Surface reservoir augmentation Blending in public water supply reservoirs before further water treatment	Health concerns Public acceptance Eutrophication (algae growth) due to nutrients	Successful practice since 1970s Multiple barrier treatment ensures safe potable water production Improvement of water quality	
	Direct potable reuse		Pipe-to-pipe blending of purified water and potable water Purified water is a source of drinking water supply blended with source water for further water treatment	Health concerns and issues of unknown chemicals Public acceptance Economically attractive in large scale reuse and chronic water scarcity Environmental buffers	Multiple barrier treatment ensures safe potable water production No health problems related to recycled water in Namibia since 1968 Cost efficient compared to indirect potable reuse

Source: author's own creation

II.3.1 New and Emerging Technologies

Innovation will play a key role for the development of circular economy with water reuse. In the next 10 to 15 years, the technology innovation in water reuse would be focused on development of reliable "practical" solutions, in order to unlock the regulatory, economic and social barriers for building cost competitive water reuse market. The major focus will be on: (1) improvement of reliability, performance, flexibility and robustness of existing technologies, (2) development of new cost effective and energy efficient technologies, (3) new tools and methods for improved water quality and process performance monitoring and (4) advancement and implementation of "soft science" innovation to resolve the socio-economic challenges of water reuse.

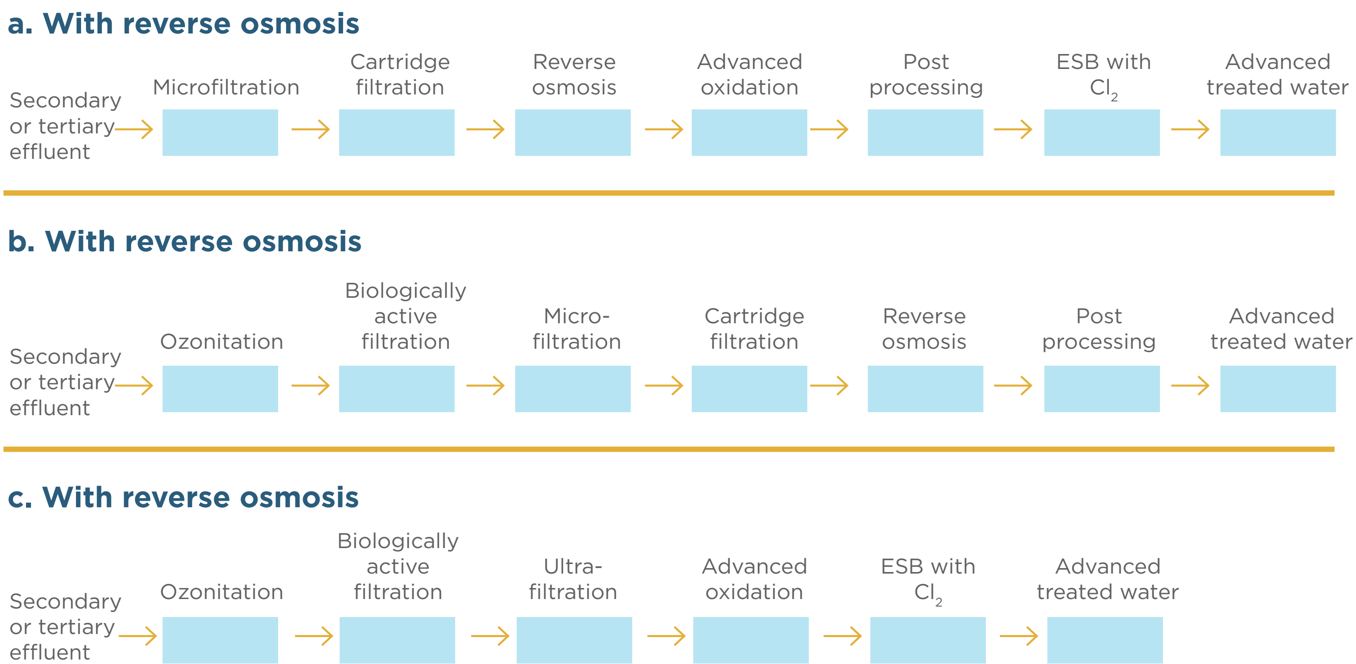
II.3.2 Direct Potable Reuse

Potable reuse is production of drinking water from highly treated municipal wastewater. Potable reuse is practiced in two forms – indirect potable reuse, where the treated municipal wastewater is conveyed to a potable water aquifer, retained in this aquifer for 6 months and then recovered from the aquifer and used as drinking water. In direct potable reuse, the highly treated wastewater is released directly into the drinking water distribution system or it is conveyed to a reservoir used for production of drinking water.

Indirect potable reuse has been practiced worldwide for over two decades. Direct potable reuse, is expected to emerge as a main source of alternative water supply by year 2030. At present, a number of US states, such as California, Texas, Arizona and Florida as well as other countries such as Israel and Australia have developed or are under way of developing regulatory framework and advanced technologies which are expected to facilitate the industry-wide adoption of direct potable reuse as alternative source of drinking water supply (US EPA, 2018).

Direct potable reuse is becoming of age worldwide because most of the economically viable non-potable reuse opportunities have already been exploited in most countries worldwide. For example, the typical cost for parallel distribution of tertiary-treated recycled water is US$0.3 to 1.7/$m^3$ whereas the typical cost for highly treated purified water, which could be delivered directly into the distribution system, is US$0.6 to 1.0/$m^3$, which is comparable to the cost of seawater desalination.

As compared to conventional drinking water plants which use source water from reservoirs, lakes and rivers, treatment plants for direct and indirect potable reuse include at least two to three additional treatment processes which serve as barriers for pathogens and trace organics and allow to consistently achieve drinking water quality (Figure 1). Dual membrane treatment by low-pressure membranes (microfiltration or ultrafiltration) and reverse osmosis, followed by advanced oxidation (e.g. ultraviolet irradiation combined with hydrogen peroxide treatment of the water) is becoming very popular and is being considered as the best available technology worldwide. The management of brine generated from the reverse osmosis treatment of the purified is the main problem for such schemes, in particular in inland locations. For this reason, an increasing interest is reported in conventional advanced treatment trains for trace organics removal by combination of ozonation, biological activated carbon, ultrafiltration or nanofiltration and advanced oxidation instead of reverse osmosis separation.



Source: Author's own creation.

Figure 1 - Technologies Most Commonly Applied for Potable Reuse

II.3.3 New Advanced Oxidation Processes

A key challenge in adopting potable reuse as a mainstream source of drinking water supply is the removal of man-made micropollutants (e.g., pharmaceuticals, endocrine disruptors, personal care products, nano-materials, perfluorinated substances) which are not easily and completely separated from the source wastewater by conventional WWTP technologies and membrane processes such as ultrafiltration and reverse osmosis. Removal of such micro-pollutants is typically achieved by advanced oxidation technologies, which combine alternative ozonation, peroxidation and UV irradiation processes (AOPs) for removal of such compounds.

Development of AOP process that has high reliability, performance, efficiency and cost-effectiveness along with simple and easy to use online monitoring of micropollutants and pathogens in the purified water are the two key obstacles to industry-wide acceptance and adoption of direct potable reuse.

The Centre for Water Research at the National University of Singapore (NUS) has developed an emerging advanced oxidation process called Electro-Fenton (He & Zhou, 2017), which received the Most Disruptive Technology Award at the 2016 Singapore International Water Week. The team's invention degrades a wide variety of contaminants, turning 99.9% of the pollutants in non-biodegradable wastewater into simpler and harmless substances such as carbon dioxide and water.

Unlike some wastewater treatment processes, it also produces virtually no sludge, has an easy plug-and-play set-up, and uses electricity instead of chemicals, making it more affordable and environmentally friendly.

II.3.4 UV-LED Systems

As indicated previously, UV irradiation is widely used in advanced oxidation systems, which a critical component of plants for indirect and direct potable reuse and is often used for disinfection of the effluent water from wastewater plants or drinking water facilities. Conventional UV systems typically utilize fluorescent lamps that contain mercury and are susceptible to breakage. The UV-LED systems are systems that contain light-emitting diodes (LEDs), which generate ultraviolet irradiation using significantly less energy than conventional UV installations (Hansen, 2016). LEDs are powered by movement of electrons in semiconductors that are incorporated into the diodes. They are smaller and more robust than conventional UV lamps, and can be configured and used in a much wider variety of applications, such as AOC systems, and ballast water disinfection.

Another drawback for traditional UV systems is the inability to turn the system on and off without diminishing the life of the lamps, which require a warm-up period before achieving full UV radiation. UV-LED systems can be turned off to save energy, and turned back on for instant operation. At present the production of UV-LED systems is more costly than conventional UV installations. However, in the next 5 to 10 years, the technology is expected to evolve into very competitive and yield significant life cycle cost savings.

II.3.5 Automated Water Quality Monitoring Systems

A critical component of the advancement of potable water reuse is the development of online monitoring instruments and software platforms that allow to identify and control water quality in real-time and to adjust the water treatment processes in response to water quality variations. Recently introduced innovative technologies, which have advanced online water quality monitoring include:

Island Water Technologies –which has developed the world's first real-time bio-electrode sensor for the direct monitoring of microbial activity in wastewater treatment systems.

Microbe Detectives - applies advanced DNA sequencing to identify and quantify nearly 100% of the microbes in a sample of water, and provides comprehensive microbial evaluations for water quality and disease management.

TECTA-PDS – has created the world's first automated microbiological water quality monitoring system, which considerably lowers the cost of monitoring.

Enabling Conditions for Water Reuse

The key issues related to the implementation of water reuse, their ranking and some of the foreseeable impediments depend on specific local conditions. The major water reuse challenges are:

- Economic viability,
- Social acceptance: public perception and support by users and local authorities,
- Policy and regulations,
- Technical issues and energy efficiency,
- Innovation and fast implementation of new tools, technologies and good practices.

Securing economic viability is an important challenge for majority of water reuse projects. Unfortunately, water reuse feasibility is often suppressed by the use of undervalued and/or subsidized conventional water resources. Full-cost recovery is a desirable objective but depends on ability to pay. The cost-benefit analysis of water reuse projects must include other management objectives and socio-environmental criteria, based on a holistic approach and catchment scale.

Similar to the development of any other utilities, the implementation of wastewater reclamation facilities generally requires a substantial capital investment. While water reuse is a sustainable approach and can be cost-effective in the long run, the additional treatment and monitoring, as well as the construction of recycled water distribution systems could be costly as compared to water supply alternatives such as imported water or groundwater. In the context of circular water economy with sustainable water resources management of the region, government grants or subsidies may be required to implement water reuse. Unfortunately, institutional barriers, as well as varying agency/community priorities, can make it difficult to implement water reuse projects in some cases.

Independent of the type of reuse application and country, public's knowledge and understanding of the safety and suitability of recycled water is a key factor for the success of any water reuse program. Consistent communication and easy to understand messages need to be developed for the public and politicians explaining the benefits of water reuse for the long term water security and sustainable urban water cycle management.

To date, the major emphasis of water reuse has been on non-potable applications such as agricultural and landscape irrigation, industrial cooling, and on residential or commercial building applications such as toilet flushing in large buildings. From these applications gray water reuse in residential and commercial buildings has not shown high promise and worldwide acceptance because of its high costs, odor emissions and complexity of the recycling and storage of gray water.

Potable reuse raises however, has been most difficult to implement worldwide, because of public concerns and the need for elaborate regulatory framework that allows to cost-effectively protect public health. The development and enforcement of water reuse standards is an essential step for the social acceptance of water recycling. However, in some cases, regulations could be a challenge and burden for water reuse, as for example in the case of very stringent requirements based on the precautionary principle. Water reuse standards must be adapted to the country's specific conditions (administrative infrastructure, economy, climate, etc.), should be economically viable and should be coordinated with country's water conservation strategy.

The technical challenges facing water reuse are not yet completely resolved. In particular, for industrial, urban and potable water reuse applications it is extremely important to improve performance, efficiency, reliability and cost-effectiveness of treatment technologies. Water recycling facilities are facing tremendous challenges of high variation of raw water quality, salinity spikes due to seawater or brackish water intrusion into sewers, as well as variation in water quantity caused by extreme conditions of very limited water demand, flooding or need for alternative disposal of recycled water.

In this context, the technology advances and innovation in the next 10 to 15 years will enable the development of reliable practical solutions, that would allow to unlock the regulatory, economic and social barriers for building cost competitive worldwide water reuse market. Key directions for innovation in water reuse technology in the next 10 years include:

1. Improvement of performance, reliability, energy efficiency and robustness of existing wastewater treatment and water reclamation processes.

2. Development of new more efficient treatment technologies with improved performance, lower carbon footprint and competitive costs. Specific focus is needed for the scale-up of new technologies.

3. Development of innovative, efficient, robust and low cost tertiary treatment (filtration and disinfection) for water reuse allowing seasonal operation for irrigation and other uses with intermittent water demand.

4. New tools and methods for monitoring of chemical and microbial pollutants and development of on-line (real-time) monitoring of water quality and process performance. A specific challenge is the monitoring of pathogens in raw wastewater and complex matrixes (sludge and soil), as well as new pollutants (nanoparticles, micro-plastics, antibiotic resistance).

5. Develop of robust database that allows for a better understanding of pathogen removal efficiencies and the variability of performance in various unit processes of multi-barrier wastewater reclamation trains.

II.4 RESOURCE RECOVERY AND ENERGY SELF-SUFFICIENCY

Resource recovery entails extraction of energy, valuable nutrients, minerals and rear earth elements from influent wastewater and sludge (biosolids) of wastewater treatment plants (WWTPs) and from concentrate (brine) generated by desalination plants. Resource recovery from wastewater and brine is a critical component of the circular economy. A recent trend is changing the view of water industry on wastewater treatment plants from facilities that process liquid waste to protect the environment into water resource recovery plants, which turn energy and organics contained in wastewater into valuable resources such as energy, fertilizers and purified water.

Energy efficiency, carbon and environmental footprint mitigation of WWTPs are expected to gain pivotal importance over the next 15 years. The ambitious goals of sustainable development and of achieving zero net carbon and pollution emission footprint of WWTP by year 2030 call for a new holistic approach to the management of the water cycle with increased role for water reuse (Lazarova, 2012). With the further growth of megacities and increasing efforts to optimize energy efficiency, water recycling is of growing interest and will take a leading role in the future of circular economy.

Technologies for energy self-sufficiency aim to recover energy contained in the influent wastewater of WWTPs and to use this energy for wastewater treatment and solids handling. In the next 10 to 15 years it is expected that a new wave of technologies will be developed, which have the potential to make the WWTPs energy self-sufficient, producing as much energy as they use. At present, most WWTPs deploy technologies that can recover energy from wastewater sludge that cover only 20 to 25% of the plant total power demand. New technologies expected to be developed by year 2020 would increase self-sufficiency to 75%, and further energy recovery and reuse technology development is projected to be able to make WWTPs 100% energy self- sufficient by year 2030 (Lazarova, 2012).

Energy self-sufficiency and sludge management are inextricably linked. The near-term goal of 75% self-sufficiency would be possible to achieve by the development of advanced technologies for harnessing the biogas generation potential of sludge. The target WWTP 100% energy self-sufficiency by year 2030 is projected to be achieved by using technologies that dramatically reduce energy use for biological wastewater treatment such as nano-size air bubble aeration systems, applying anaerobic treatment processes such as Anammox, as well as using solar and heat power generation systems installed at the WWTP site.

II.4.1 New and Emerging Technologies

Over the next 10 to 15 years, the wastewater management innovations will focus on advanced membrane-based treatment technologies, anaerobic digestion of sludge, energy reduction for wastewater treatment, and new membranes from biomaterials. Aerobic granulation, for instance, is touted as the future standard for industrial and municipal wastewater treatment due to its energy-effectiveness and cost-efficiency. It has also been noted that plate and frame membrane bioreactor (MBR) systems with higher permeability, less biofouling and outstanding chemicals and temperature resistance will become mainstream wastewater treatment and resource recovery technology by year 2030 (Luo et al., 2017).

II.4.2 Phosphorus Recovery from WWTP sludge

Sludge generated from the WWTP processes contains valuable nutrient – phosphorus, which could be recovered and organo-mineral fertilizer. A number of wastewater treatment plants in Europe at present are planning or already applying phosphorous recovery installations, which incorporate technologies such as crystallization reactors that precipitate the phosphorus contained in the liquid sludge as a phosphorous mineral compound – struvite, or in the sludge ash, if the sludge is dewatered and incinerated. In addition of recovery of valuable nutrient, the removal of phosphorus from the sludge in the form of struvite reduces operational costs because it significantly reduces the scaling problems caused by struvite on the downstream piping and equipment processing sludge by anaerobic digestion. Germany has taken a leading position in this initiative and a number of other countries in central and northern Europe are expected to follow suit in the next five years.

II.4.3 Enabling Conditions for Resource Recovery

Recently adopted regulations in Germany, Switzerland and Austria mandate phosphorus recovery from wastewater sludge, thereby promoting the recovery of this valuable resource. These regulations are essentially phasing out land application of nearly all use of sludge from WWTPs and mandating phosphorus recovery from this sludge by 2029 for plants over 100,000 people equivalents (p.e.) and by year 2032 for plants serving over 50,000 p.e..

While technologies for extraction of valuable nutrients such as phosphorus already exist, the regulations allowing the use of the recovered nutrients as fertilizers are still under development or non-existent. The European Union (EU) currently is developing revised Fertilizer regulations, which are expected to shorten and simplify the path of the use of products, made from secondary raw materials such as organic and organo-mineral fertilizers, composts and digestates. These regulations are expected to be promulgated by the end of 2018. Two to three more years will be needed before the regulations apply and these products are EU certified for safe use.

New technologies are aimed at reducing energy consumption (by 20 to 35%), reducing capital costs (by 20 to 30%).

Anammox Anaerobic Wastewater Treatment

Anammox stands for Anaerobic Ammonium Oxidation. The process was discovered in the early nineties and has great potential for the removal of ammonia nitrogen in wastewater. The responsible bacteria transform ammonium (NH_4^+) and nitrogen dioxide (NO_2) into nitrogen gas (N_2) and water (H_2O). This saves costs as less energy for aeration and no organic carbon sources (e.g. methanol or recirculated sludge) are required. During the last 20 years, many research projects were conducted on the Anammox process. In 2007, the first large-scale Anammox reactor was built in Rotterdam. It displays the vast possibilities of this new process. It is expected that this game-changing disruptive technology will become a mainstream wastewater process in majority of WWTPs by year 2030.

II.5 DESALINATION

Over the past decade seawater desalination has experienced an accelerated growth driven by advances in membrane technology and material science. Recent technological advancements such as pressure-exchanger based energy recovery systems, higher efficiency reverse osmosis (RO) membrane elements, nanostructured RO membranes, innovative membrane vessel configurations, and high-recovery RO systems, are projected to further decrease the energy needed for seawater desalination and be a backbone for disruptive decease in the cost of fresh water produced by desalination of saline sources (seawater, brackish water and treated wastewater).

The steady trend of reduction of desalinated water production energy and costs coupled with increasing costs of conventional water treatment and water reuse driven by more stringent regulatory requirements, are expected to accelerate the current trend of reliance on the ocean as an attractive and competitive water source. This trend is forecasted to continue in the future and to further establish ocean water desalination as a reliable drought-proof alternative for majority of the coastal communities worldwide in the next 15 years. While at present, desalination provides approximately 10% of the municipal water supply of the urban coastal centers worldwide, by year 2030 this percentage is expected to reach 25% (GWI, 2017).

II.5.1 New and Emerging Technologies

Near and long-term desalination technology advances are projected to yield significant decrease in costs of production of desalinated water by year 2030. In desalination, innovative technologies have been addressing longstanding issues that have hampered the development of this alternative resource. New technologies are aimed at reducing energy consumption (by 20 to 35%), reducing capital costs (by 20 to 30%), improving process reliability and flexibility, and greatly reducing the volume of the concentrate (brine) discharge. Some of the technologies with high cost-reduction potential are equally suitable for desalination and advanced wastewater treatment for reuse are discussed below.

Nano-structured Membranes

A recent trend in the quest for lowering the energy use and fresh water production costs for desalination is the development of nanostructured (NST) RO membranes, which provide more efficient water transport as compared to existing conventional thin-film membrane elements (Bargasan, 2018).

The salt separation membranes commonly used in RO desalination membrane elements today are dense semi-permeable polymer films of random structure (matrix), which do not have pores. Water molecules are transported through these membrane films by diffusion and travel on a multi-dimensional curvilinear path within the randomly structured polymer film matrix. This transport is relatively inefficient in terms of membrane film volume/surface area and substantial energy is needed to move water molecules through the RO membranes. A porous membrane structure, which facilitates water transport would improve membrane productivity.

NST membranes are RO membranes which contain either individual straight-line nanometer-size channels (tubes/particles) embedded into the random thin-film polymer matrix, or are entirely made of clustered nano-size channels (nanotubes). NST membrane technology has evolved rapidly over the past 10 years and recently developed nanostructured membranes either incorporate inorganic nanoparticles within the traditional membrane polymeric film or are made of highly-structured porous film which consists of densely packed array of nanotubes. These nanostructured membranes reportedly have much higher specific permeability than conventional RO membranes at practically the same high salt rejection. In addition, nanostructured membranes have comparable or lower fouling rate than conventional thin-film composite RO membranes operating at the same conditions, and they can be designed for enhanced rejection selectivity of specific ions.

For example, a US membrane supplier NanoH_2O, recently acquired by LNG, has developed thin-film nano-composite (TFN) membranes, which incorporate zeolite nanoparticles (100 nanometers in diameter) into a traditional polyamide thin membrane film. These new TFN membranes have been commercially available for seawater applications since September 2010. The new membrane elements have 10 to 20% higher productivity than other currently available RO membranes or to operate at approximately 10% to 15% lower energy use while achieving the same productivity as standard RO elements (Gude, 2016).

Over the last 5 years, researchers worldwide have focused on the development of RO membranes made of vertically aligned densely packed array of carbon nanotubes (CNT) which have the potential to enhance membrane productivity up to 20 times as compared to the state-of-the-art desalination membrane elements available on the market at present. While CNT based desalination membranes are not commercially available as of yet, it is very likely that such membranes will be released for full-scale application by year 2030. Recently, grapheme has been focus on significant research efforts because compared to nanotubes and carbon fiber it has a higher aspect ratio and surface area, which infers higher permeability and salt rejection, and lower fouling propensity.

Nano-structured membranes hold the greatest potential to cause a quantum leap in desalination cost reduction because theoretically, they can produce an order of magnitude more fresh water from the same membrane surface area, than the state-of-the-art RO membranes commercially available on the market at present. Such dramatic decrease in the membrane surface area needed to produce the same volume of desalinated water could reduce the physical size and construction costs of membrane desalination plants over two times and bring this cost of production of desalinated water production to the level of that of conventional water treatment technologies.

A potential challenge with higher productivity membrane elements is that their efficiency and productivity due to fouling of the membrane surface because the rate of fouling will increase proportionally to the rate of membrane fresh water productivity (membrane permeate flux). Therefore, the development of higher productivity membranes would likely require the modification of the membrane structure, geometry and the configuration of the entire RO system to combat the accelerated fouling and scaling processes that accompany the use of membrane of fluxes that are significantly higher than these of RO systems with conventional membrane elements. A step forward in this direction is the use of close-circuit desalination systems which allow to lower the membrane fouling rate by the slow increase in RO system recovery rate via concentrate recirculation loop.

Forward Osmosis (FO)

In forward (direct) osmosis a solution with osmotic pressure higher than that of the high-salinity source water ("draw solution") is used to separate fresh water from the source water through a membrane. Forward osmosis process holds the potential to reduce energy use for salt separation. A number of research teams in the US and abroad are working on the development of commercially viable FO systems. These systems mainly differ in chemical composition of the draw solution and the method of recovery of the draw solution from the desalinated water.

Existing conventional thin-film composite RO membranes are not suitable for FO applications mainly due to their structure, which leads to low productivity. Development of high-productivity low-cost FO membrane elements of standard size is one of the current greatest challenges and most important constraints in creating commercially-viable FO systems that could ultimately replace exiting RO systems while reusing most of the existing RO system equipment. Most of the existing full-scale installations applying forward osmosis have been used mainly for industrial reuse. The use of this technology for drinking water applications is under development but from a total energy use point of view may not provide a significant competitive advantage to RO because of the high energy demand needed to separate the draw solution from the FO permeate to an extent where this permeate can meet potable water quality requirements.

Several companies such as Modern Water, Hydration Technology Innovation, and Trevi Systems have developed commercially available FO membrane desalination technologies, which to date have only found application for treatment of wastewaters from oil and gas industry and high salinity brines. The Trevi systems FO technology is of potential interest because it uses draw solution that can be reused applying solar power – it is the main innovative technology considered for the ongoing solar power driven desalination research led by Masdar in the United Arab Emirates.

The main potential benefit of the development of commercially viable FO technologies for production of desalinated water is the reduction of the overall energy needed for fresh water production by 20 to 35%, which energy savings could be harvested if the draw solution does not need to be recovered and the salinity of the source water is relatively high. Such energy reduction could yield cost of water reduction of 20 to 25% by year 2030, especially for non-drinking water production applications (Hillal et al., 2018).

Membrane Distillation (MD)

In membrane distillation water vapor is transported between "hot" saline stream and "cool" fresh water stream separated by a hydrophobic membrane. The transport of water vapor through the membrane relies on a small temperature difference between the two streams. There are several key alternative MD processes, including air-gap, vacuum and sweeping gas membrane distillation.

The sweeping-gas MD has been found to be more viable than the other alternatives. A sweeping-gas is used to flush the water vapor from the permeate side of the membrane, thereby maintaining the vapor pressure gradient needed for continuous water vapor transfer. Since liquid does not permeate the hydrophobic membrane, dissolved ions/non-volatile compounds are completely rejected by the membrane.

The separation process takes place at normal pressure and could allow achieving approximately two times higher recovery than seawater desalination (80% vs. 45 to 50%). It is also suitable for further concentration of RO brine from (i.e., concentrate minimization). Membranes used in MD systems are different from the conventional RO membranes – they are hydrophobic polymers with micrometer-size pores. However, flux and salt rejection of these membranes are usually comparable to these of brackish water RO membranes (Alkhudhiri et al., 2012).

Currently, MD enjoys a fairly high academic interest because of its very high recovery (as compared to RO) and lower energy use (as compared to conventional thermal evaporation technologies). The viability of this technology hinges upon the development of contactor geometry that provides extremely low-pressure drop and on the creation of membranes, which have high temperature limits. Because of its current limitations, membrane distillation holds promise mainly for concentrate minimization and for fairly small size applications. However, this technology has potential to be scaled up and become a mainstream process widely used for desalination, industrial water reuse and brine management by year 2030.

At present, MD systems are commercially available from Memsys, which have focused the advancement of this technology application mainly for treatment of produced water waste streams from oil and gas industry. Other companies, such as Memstill, Keppel Seghers, and XZERO MD have recently commercialized MD systems mainly for industrial wastewater treatment and reuse applications. The main cost savings that can result from the application of this technology for large-scale desalination plants is lowering the cost of fresh water production from highly saline seawaters such as these of the Arabian Gulf and the Red Sea and the costs for concentrate management and disposal for brackish desalination plants and RO systems used for potable reuse by 15 to 20%. Commercialization and industry-wide adoption of such systems is highly likely to transform the water industry by year 2030.

Electrochemical Desalination

Developed by Evoqua (formerly Siemens) under a Challenge Grant from the Government of Singapore, this continuous electrochemical desalination process is based on combination of ultrafiltration pretreatment, electrodialysis (ED) and continuous electrodeionization (CEDI) and is claimed to desalinate seawater to drinking water quality at only 1.5 kWh per cubic meter. This energy consumption is lower than the energy use of conventional SWRO desalination systems.

The electrochemical desalination has two key advantages as compared to RO desalination (1) it does not require high pressure for desalination and therefore the equipment and materials used for the process are mechanically and structurally less demanding and therefore, less costly; (2) the ED process is more efficient by its nature, because it separates and moves a much smaller mass of material (ions of salts) through low pressure membranes as compared to RO membrane separation where much larger number of water molecules are moved through thicker and more robust and complex high pressure membranes. Although thermodynamically the theoretical amount of minimum energy needed for separation is the same, the auxiliary energy use inherently is lower when a process moving smaller mass of matter is used.

This process is currently under full-scale development and has been able to achieve energy consumption of 1.8 kWh/m^3 when desalinating seawater of salinity of 32,000 mg/L at 30% recovery. The process operates at low pressure (2.8 to 3.4 bars), the equipment can be produced from plastic, and the membranes used for ED and CEDI are chlorine resistant. The potential reduction of desalinated water costs this technology can yield is 15 to 20% by year 2030 (Shaw et al., 2011).

Capacitive Deionization (CDI)

This technology uses ion transport from saline water to electrodes of high ion retention capacity, which transport is driven by a small voltage gradient. The saline water is passed through an unrestricted capacitor type CDI modules consisting of numerous pairs of high-surface area electrodes. Anions and cations contained in saline source water are electrosorbed by the electric field upon polarization of each electrode pair by a direct current (DC) power source. Once the maximum ion retention capacity of the electrodes is reached, the de-ionized water is removed and the salt ions are released from the electrodes by polarity reversal.

The main component, which determines the viability of the CDI, is the ion retention electrodes. Based on research to date, carbon aerogel electrodes have shown to be suitable for low salinity applications. This technology holds promise mainly for RO permeate polishing and for low-salinity brackish water applications. The fresh water system recovery for such applications is over 80%.

With recent development of new generation of highly efficient lower-cost carbon aerogel electrodes, CDI may out-compete the use of ion exchange and RO for generation of high purity water. Several commercially available CDI systems are available on the market (Enpar, Aqua EWP, Voltea). However, these systems have found applications mainly for small brackish water desalination plants and mainly industrial applications due to the limited specific ion adsorption of current carbon materials.

The technology holds promise because it could theoretically reduce the physical size and capital costs of desalination plants with over 30%. Current carbon electrode technology however limits salt removal to only 70 to 80%, uses approximately two times more energy than conventional RO systems and is subject to high electrode cleaning costs due to organic fouling. New electrode materials as grapheme and carbon nanotubes may potentially offer solution to the current technology challenges and are very likely to become readily available by year 2030.

Biomimetic Membranes

Development of membranes with structure and function similar to these of the membranes of living organisms (i.e., diatoms) may offer the ultimate breakthrough for low-energy desalination (specific energy use below 2.0 kWh/1,000 gallons). In these membranes water molecules are transferred through the membranes through a series of low-energy enzymatic reactions instead of by osmotic pressure. The permeability (e.g., the volume of fresh water produced by unit surface area) of such membranes could theoretically be 5 to 1000 times higher than that of currently available RO membranes (Giwa et al., 2017).

Aquaporins are example of such membrane structures. They are proteins embedded in the cell membrane of many plant and animal tissues and their primary function is to regulate the flow of water and serve as "the plumbing system for cells". While osmotic pressure driven exchange of water between the living cells and their surroundings are often the key mechanism for water transport, aquaporins provide an alternative mechanism of such transport.

Aquaporins selectively conduct water molecules in and out of the cell, while preventing the passage of ions and other solutes. Also known as water channels, aquaporins are integral membrane pore proteins. Some of them transport also other small, uncharged solutes, such as glycerol, CO_2, ammonia and urea across the membrane, depending on the size of the pore. However, the water pores are completely impermeable to charged species, such as protons.

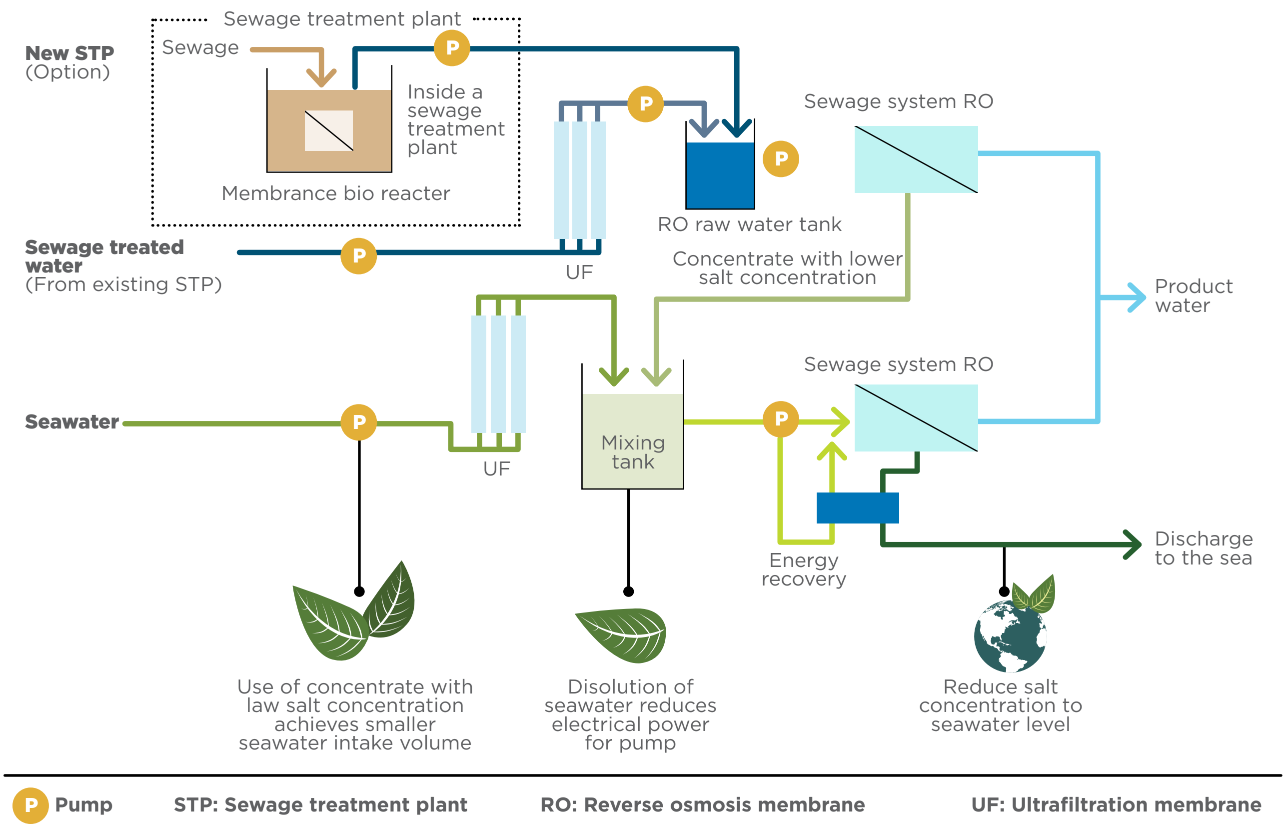
One key advantage of aquaporin-based membranes, which is not found in conventional RO membranes, is that they combine both the ability to have high permeability and to exhibit high salt rejection at the same time. Conventional RO elements have inverse relationship between permeability and salt rejection. The smaller the molecular pores of the higher the salt rejection of the RO membranes but the lower the membrane permeability and vice versa. So practically, it is not possible to create a RO membrane that has high salt rejection and high productivity at the same time.

Currently researchers at the US, Singapore and Australia are focusing on advanced research in the field of biomimetic membranes and in July 2018, the company Aquaporin introduced the first commercial FO membrane with embedded aquaporins. These aquaporins are installed into spherical artificial vesicles referred to as polymersomes, which are incorporated on the surface of the conventional membranes. Such aquaporin-enhanced membranes are expected to operate at low feed pressures (5 to 15 bars) and to yield significant energy savings and enhanced fresh water production.

Although this research field is projected to ultimately yield high-reward benefits (e.g., overall desalinated water cost and energy use reduction with over two times), currently it is in early stages of development – further research is focused on the formation and production of aquaporin structures, which are incorporated into robust and durable commercial membranes – such products are expected to be commercialized by year 2030 (Thang et al., 2012).

Joint Desalination and Water Reuse

A new trend towards adopting the One-Water concept is the development of technologies for joint desalination and water reuse, where the desalination plant and the potable reuse plant are combined into One-Water Plant producing drinking water at disruptively (25 to 35%)



Source: Voutchkov, Nikolay. Desalination Project Cost Estimating and Management. 1st ed., CRC Press, 2018

Figure 2 – One-Water System for Joint Desalination and Reuse

lower cost as compared to seawater desalination alone. The One-Water technologies, such as that presented in Figure 2 present an opportunity for reduction of the energy and cost needed for desalination by feeding highly treated secondary effluent or RO reject from wastewater treatment plant into the feed water of SWRO desalination plant. Because the discharge from advanced water reclamation plants has an order of magnitude lower salinity than the source seawater, the SWRO system's feed water salinity and energy cost for desalination could be reduced by 20% or more. Such treatment process is referenced as joint desalination and water reuse or One-Water process. An example of such joint desalination and water reuse facility is the Hitachi's Remix system, which has been extensively tested at the 40,000 m^3/day Water Plaza Advanced Treatment Plant in Japan (Kurihara & Takeuchi, 2018).

At present, joint desalination and reuse is in its infancy and its practical implementation to date has been exclusively for industrial water supply. The use of joint desalination and water reuse systems for production of drinking water requires further development as well as promulgation of regulations for direct potable reuse.

However, as direct potable reuse matures and gains worldwide acceptance in the next 10 years, joint desalination and water reuse facilities are likely to become a mainstream trend and attractive low-energy alternative for production of desalinated water. The benefits and potential challenges of joint desalination and reuse plants in terms of efficiency, reliability, costs and product water quality are currently undergoing thorough investigation in demonstration plants in Japan and South Africa.

II.5.2 Enabling Conditions for Desalination

The advance of the reverse osmosis desalination technology is closest in dynamics to that of the computer technology. While conventional technologies, such as sedimentation and filtration have seen modest advancement since their initial use for potable water treatment several centuries ago, new more efficient seawater desalination membranes and membrane technologies, and equipment improvements are released every several years. Similar to computers, the RO membranes of today are many times smaller, more productive and cheaper than the first working prototypes. The future improvements of the RO membrane technology which are projected to occur by year 2030 are forecasted to encompass:

- Development of Membranes of Higher Salt and Pathogen Rejection, and Productivity; and Reduced Trans-membrane Pressure, and Fouling Potential;
- Improvement of Membrane Resistance to Oxidants, Elevated Temperature and Compaction;
- Extension of Membrane Useful Life Beyond 10 Years;
- Integration of Membrane Pretreatment, Advanced Energy Recovery and SWRO Systems;

- Integration of Brackish and Seawater Desalination Systems;
- Development of New Generation of High-Efficiency Pumps and Energy Recovery Systems For SWRO Applications;
- Replacement of Key Stainless Steel Desalination Plant Components with Plastic Components to Increase Plant Longevity and Decrease Overall Cost of Water Production.
- Reduction of Membrane Element Costs By Complete Automation of the Entire Production and Testing Process;
- Development of Methods for Low-Cost Continuous Membrane Cleaning Which Allow to Reduce Downtime and Chemical Cleaning Costs;
- Development for Methods for Low-cost Membrane Concentrate Treatment, In-Plant and Off-site Reuse, and Disposal.

Although, no major technology breakthroughs are expected to bring the cost of seawater desalination further down dramatically in the next several years, the steady reduction of desalinated water production costs coupled with increasing costs of water treatment driven by more stringent regulatory requirements, are expected to accelerate the current trend of increased reliance on the ocean as an attractive and competitive water source by year 2030.

This trend is forecasted to continue in the future and to further establish seawater desalination as a reliable drought-proof alternative for many coastal communities worldwide. These technology advances are expected to ascertain the position of SWRO treatment as viable and cost–competitive processes for potable water production and to reduce the cost of fresh water production from seawater by 25% in by year 2022 and by up to 60% by year 2030 (see Table 2).

The rate of adoption of desalination in coastal urban centers worldwide would be highly dependent on the magnitude of water stress to which they are exposed and availability of lower-cost conventional water resources.

In the future, desalination is likely to be adopted as main water supply in most arid and semi-arid regions of the world such and the Middle East, North Africa, the Western United States, and Australia and in locations of concentrated industrial demand for high quality water such as Singapore, China, and Northern Chile.

II.6 SUMMARY AND CONCLUSIONS

While the water industry faces diverse challenges it is making significant progress towards finding cost effective and sustainable water management solutions and disruptive technologies, which by year 2030 are expected to transform water management and elevate its reliance on alternative water resources such as water reuse and desalination. Water professionals worldwide are united in building a future where water is recognized and treated as precious, highly valuable resource, and as a cornerstone of circular economy.

Table 2
Forecast of Desalination Energy Use and Costs for Medium and Large Plants

Parameter for Best-in Class Desalination Plants	Year 2018	Year 2022	Year 2030
Total Electrical Energy Use (kWh/m^3)	3.5 – 4.0	2.8 – 3.2	2.1 – 2.4
Cost of Water (US$/$m^3$)	0.8 – 1.2	0.6 – 1.0	0.3 – 0.5
Construction Cost (US$/MLD)	1.2 – 2.2	1.0 – 1.8	0.5 – 0.9
Membrane Productivity (m^3/membrane)	28-48	55-75	95-120

Source: author's own creation

The main transformational change of the water industry is that it is entering a new era of water management where the old barriers of water and wastewater are slowly fading and where water in all of its states is looked upon as a valuable commodity and precious resource that has to be closely monitored, digitalized, accounted for, and reused rather than being considered just a simple source of supply or waste that has to be disposed of.

Traditionally water utilities have managed water supply and treatment of wastewater, minimizing the impact on the environment by removing nutrients and using the waste generated in a beneficial manner. In order to adopt to the challenges they face in the next 10 to 15 years, utilities have to develop diversified portfolio of water supply in which conventional and direct potable water reuse and desalination have comparable share to that of conventional water treatment sources such as rivers, lakes and dams. In order for such fundamental transformation of the water industry to occur by year 2030, the fundamental legal framework, which currently regulates water and wastewater separately (e.g., in the US they are regulated by the Safe Drinking Water Act and the Clean Water Act) has to be transformed into a unified One-Water Act that recognizes water as a valuable resource in all of its forms and uses.

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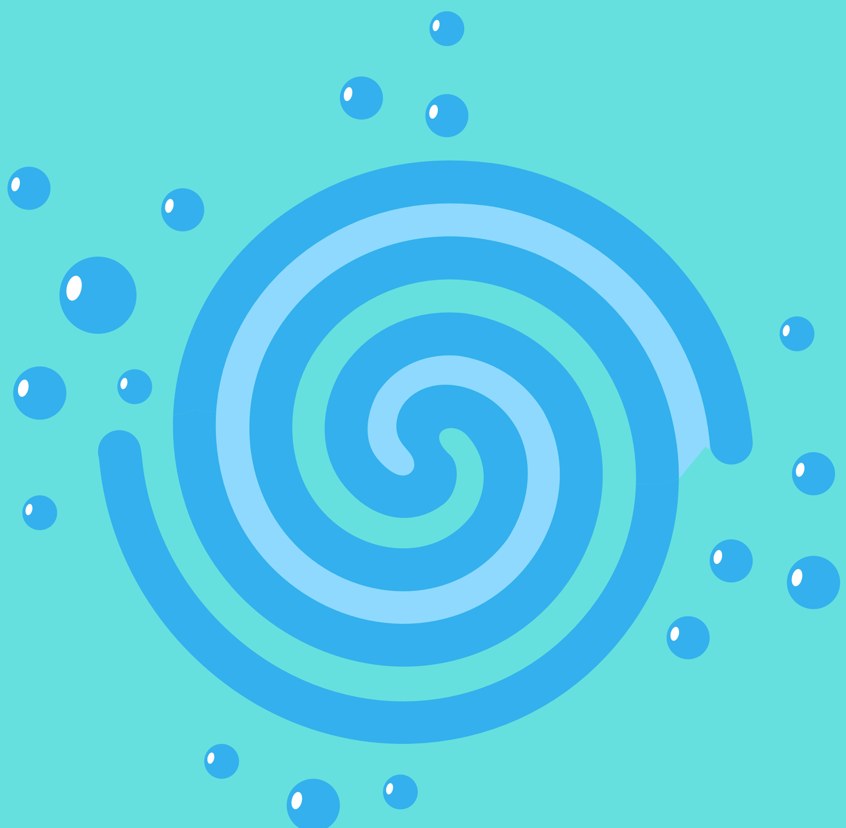
III. Positive Water Sector Disruptions by 2030



III.1 Overview

Water security has emerged as a global concern over the last two decades. This creates the impetus for a broad range of innovations that should disrupt water and wastewater services. The most significant disruption I expect to see is that a much greater role will emerge for the private sector, which will in turn modify processes in use by this public sector dominated area. This will come through: the provision of water and wastewater services, from the bottom up – highly decentralized yet networked solutions;

1. the use of financial instruments to securitize water, climate and environmental risks;

2. management services that try to leverage the value of water for other sectors, such as mining, energy and agriculture; and

3. pressure for reforms in regulatory processes that lead to adaptive environmental and resource management that is informed by data, active trend mapping and attribution.

4. Increasing concern with climate variability and change, as climate extremes coupled with existing stresses lead to an increasing demand for adaptation and risk mitigation for supply chains, cities and populations.

Absent the role of the private sector, NGOs and finance/development organizations, given the conservative nature of the water sector it is not likely that tremendous changes will emerge by 2030. In the sections that follow, potential disruptive strategies (ones that would significantly change the way things are done now, and translate into higher water system effectiveness and resilience) are sketched for 3 areas:

1. **Water and Wastewater systems:** revolutionary decentralized networks with remote sensing and control of water quantity and quality parameters, ability to use rainwater, surface, ground water or wastewater as source water, and assure safe, affordable drinking water at the point of use.

2. **Flood & Drought Risk:** The use of parametric financial instruments such as index insurance to address preparation, as well as rapid response to climate extremes

to help leverage probabilistic seasonal and longer climate forecasts for risk prediction, water allocation and system operation.

3. **Environmental Management and Regulation:** The intersection of the engagement of Environmental NGOs with watershed stakeholders, and Green Bonds issuers to devise participatory, adaptive approaches for monitoring and investment in watershed services that address the cumulative effects of human use on water quantity and quality in a changing world. A significant departure from the current resource allocation and environmental permitting and regulation model may emerge.

III.2. WATER AND WASTEWATER SYSTEMS

Large, centralized infrastructure systems were developed in the 20th century for storage, treatment and distribution of piped water, and for the collection, treatment and disposal of wastewater in urban areas. Economies of scale, and the need for specialized technicians to operate such systems led to the development of such systems. Typically, projections of future population growth and demand 10-30 years into the future are made when such systems are being planned, leading to designs that are oversized relative to the demand when implemented. The capital costs of these systems are consequently high and require financing for most communities. Since these are upfront costs, they determine the financial viability of the projects.

Several challenges are now seen with such infrastructure. The maintenance and operation of the systems is usually expensive, especially when they are oversized. Concerns as to raising water and wastewater rates lead to financial constraint. As a result, maintenance and upgrades are deferred and the systems degrade over time, in developed as well as developing countries. The

USA currently faces a challenge of finding nearly $1 trillion to replace aging water and wastewater infrastructure. Water and wastewater leaks are common, and given the low price charged for water, often addressing leakage is more expensive than the value of water loss in the system.

Further, as has been illustrated by the serious issues with lead in drinking water in Flint, Newark, Pittsburgh, Chicago, Philadelphia and elsewhere, even in first world settings there is no assurance that water delivered to the consumer will meet safe drinking water standards even if the water produced at the treatment plant does. In developing countries, such as India, piped water supplies from the public system are intermittent – an hour or two in the morning and a similar duration in the evening. Affluent consumers use PVC storage units augmented by pumps in their houses, and RO systems for water purification in the kitchen to adapt to this situation. This translates into a private expense in a personal water system for some and lack of service for others. Even so, there is no testing or verification of the drinking water quality.

Israel, Australia and parts of India now mandate that property owners capture rain water and store or recharge it. Many countries practice rainwater harvesting or capture in urban areas and wetlands to recharge aquifers or even to alleviate floods. However, examples of systems that allow the integration of piped, centralized systems and rain water systems are few. Typically, rivers, lakes and aquifers are primary water sources.

Wastewater treatment systems discharge treated effluent into rivers or lakes, and in the process many chemicals whose effects on aquatic species may or may not be known are discharged (Oakley, Gold, & Oczkowski, 2010). Biological systems used for wastewater treatment can be energy intensive and also require relatively large land areas. The current thinking is that wastewater should be seen as a resource and purified water as well as energy and other products should be recovered from it, in the spirit of a circular economy.

Decentralized wastewater treatment systems have also been promoted in many areas. Their potential advantage is that they can be added as needed, and do not require the potentially large investment in sewer systems and pumping. A traditional example is the use of septic tanks with or without additional treatment. The success of such systems has been quite mixed (Naik & Stenstrom, 2016). They require periodic renewal at an expense comparable to the original cost. They can lead to high nutrient loadings to groundwater, unless the density is rather low. Nitrogen control for septic systems has also been explored and several solutions have been identified, but have met with a variety of reliability challenges in real world applications (Oakley et al., 2010)(Iribarnegaray, Rodriguez-Alvarez, Moraña, Tejerina, & Seghezzo, 2018). Newer decentralized systems consider constructed wetlands (Machado, Beretta, Fragoso, & Duarte, 2017) as well as membrane bioreactors and miniaturized versions of centralized wastewater systems. The membrane based and miniature systems can also include thermal exchange and energy recovery.

Wastewater treatment and reuse occurs indirectly nearly everywhere where the drinking water source is downstream of another town's wastewater (treated or not) discharge (Rice & Westerhoff, 2015). Direct treatment and re-use directly from the wastewater has largely been for agricultural or non-potable water use. Exceptions include Singapore, Texas, California, Namibia, Jordan, India, Australia, and the Philippines, where the treated wastewater may be used directly, or used to recharge an aquifer for subsequent withdrawal. Drinking water is typically a very small fraction of even household water use, and consequently, even if energy intensive technologies such as nanofiltration are used to finally purify treated wastewater, the total expense for treatment will be significantly lower than the cost of bottled water.

To summarize, centralized systems have high capital costs, and face maintenance challenges to preserve the integrity of the network. Decentralized systems, enabled by digital technologies (e.g., real time monitoring) can be added as needed, and locally maintained, but posed high transaction and reliability challenges for the operators in the past. In both cases, at present the quality of the water provided at the point of use is not pervasively tested or assured. Wastewater reuse is feasible, and the level of treatment needed may depend on the intended (re-)use.

III.2.1 Potential Disruption

Smart Decentralized Networks

In a utopian world, one would be able to use any local water source – rain water, surface water, ground water or "wastewater", assure its storage, including during droughts, treat it and supply it locally at an affordable cost with high reliability as to quantity and quality at the point of use. In this paper, the argument is that such a utopia may soon be technically and economically achievable, in much the same way that solar electricity has emerged as a decentralized, renewable energy source with widespread application at different scales, with an accompanying growth of the private sector and service industry.

Examples of pioneering companies who are leading the way for such a disruption include Natural Systems Utilities (NSU), based in New Jersey, and Ketos, based in California. NSU has developed and operated onsite water and wastewater treatment and reuse systems in a variety of settings including dense urban infill buildings, and resorts for more than the past 20 years. The systems installed in several high rise buildings in New York City are fully automated, and remotely monitored and treat wastewater to near drinking water quality at a unit cost that is competitive with centralized wastewater systems. Ketos focuses on real time, automated and smart-connected monitoring of water quantity and quality. Research in this area is getting to the point that many of the key contaminants of interest can be sensed in real time and in-pipe, and the information can be transmitted to central servers for processing and response (Besmer et al., 2016; Cogan et al., 2015; Lambrou, Anastasiou, Panayiotou, & Polycarpou, 2014; Lin, Li, & Burns, 2017; Maity et al., 2017; Shahat et al., 2015; J. P R Sorensen et al., 2015; James P.R. Sorensen et al., 2018; Verma & Gupta, 2015; Zamyadi, Choo, Newcombe, Stuetz, & Henderson, 2016; Zhou et al., 2018). Ketos is developing such an ecosystem. These are just two of many companies that are developing similar products, including units of major corporations such as Fluence, Xylem, Veolia and Suez. Others of note are Aqwise, and Organica Water.

A large number of vendors including Suez, Veolia, Waterfleet, Applied Membranes, Aquamove, Culligan Matrix Solutions, and Envent have mobile water treatment operations that brings the treatment plant to the site. This is a rapidly growing area that serves the hydraulic fracking industry, military operations, and emergency relief for plant failure or after natural disasters. A range of technologies ranging from filtration membranes to reverse osmosis to ion exchange to electrocoagulation are in use, with scales that could serve a small cluster of houses all the way to neighborhoods (Griffith, Shumakov, Akbayev, & Fejervary, 2015; Moro, 2018; Park, An, Park, & Oh, 2015; Ramli & Bolong, 2016; Yu, Choi, Choi, Choi, & Maeng, 2018). Quotations for water and wastewater treatment from several of the mobile operators translate into numbers that are very competitive with current water charges.

(Ennenbach, Concha Larrauri, & Lall, 2018) show that residential water demand could be met with greater than 90% reliability over much of the USA from rainwater collected from the typical roof area. Rainwater was used to serve the typical home demand in each county in the USA, considering over 60 years of daily climate data, and a 70% reuse of the wastewater generated domestically. In related, unpublished work, the technical and economic feasibility of rainwater collection and use at large buildings in Mexico City was demonstrated, even factoring in the current subsidies for water costs. Where, the subsidies are not considered, rainwater harvesting and local potable and non-potable use becomes competitive. Given the grave water, flooding and wastewater situation in Mexico City, a strategy that embodied decentralized networks, at neighborhood and/or building scales, and leveraged rain water collection, storm water collection and wastewater collection locally could be very effective. Parking structures and roofs installed with solar panels could also double as water collection systems, and local storage could be created using existing domestic and public tanks as well as subsurface tanks in areas with parks.

The convergence of the following elements translates into a strategy for the disruption of the water and wastewater systems:

- The high cost structure and performance of existing centralized systems, and their operation largely in the public sector or by private companies.

- The need for infrastructure renewal, and new infrastructure globally, that comes with a high financing need, and questions as to affordability.
- The availability of real time water quality, system integrity monitoring and remote control to assure point of use performance.
- The availability of a range of advanced, yet affordable water and wastewater treatment systems that cover different scales and contaminants, and could be operated remotely and semi-automatically.
- The potential to develop and add decentralized networks of systems as needed instead of developing a large, oversized system at the outset. This translates into an economic advantage, that is further enhanced by the reduction in hard infrastructure needed for piping and pumping, and by the ability to rapidly deploy replacement systems with lower operating costs, and economies of scale derived through mass manufacturing. This economic efficiency translates into faster return on investment and efficiency in capital deployment, leading to easier financing.
- The large number of small and large companies and innovators entering this space
- Successful examples of business models for decentralized treatment systems at some scales. Pilots to assess best scales and network designs are still needed.
- The willingness of middle and higher income consumers and corporations to embrace alternatives to traditional water utilities by installing their own treatment and storage systems that are serviced by third parties.
- Much higher sustainability and resilience given the ability to develop effective water reuse strategies, including thermal energy exchange, thus reducing outflows and pollution to water bodies, as well as intake of water from natural water bodies. This translates into higher ecological performance and eligibility for impact investing.
- Substantially lower and more efficient utilization of real estate by smaller systems that can be installed in building basements or below grade in parks and green space.

The obstacles to the disruption are similar to what was experienced in the electricity industry. Large scale centralized electric system operators, initially did not respond to the opportunity of solar and other renewable sources, and were primarily concerned with revenue loss. Subsequently, as the prices for delivered solar and wind systems dropped, operators started considering these alternatives, but in many cases still want control so that they can assure grid reliability. The water situation is more complex, since there are rarely national or regional water utilities, and local utilities have little interaction with each other, or innovation potential and hence tend to be insular and resistant to change. They have used health concerns as an issue to block on site wastewater treatment and use as drinking water, and have generally resisted decentralized systems as well as pervasive real time monitoring. They have embraced digital metering and smart metering for leak detection, as these show promise for revenue enhancement. It would be quite reasonable to integrate remote water quality sensing at the point of use directly into emerging smart meters. This may start happening at utilities where significant drinking water quality concerns emerge. (Allaire, Wu, & Lall, 2018) find significant increases in safe drinking water violations in the USA, especially in rural and smaller communities, where the financial health of the utilities is also a concern.

Companies such as Rotoplas in Mexico are well primed to develop such a convergent strategy for decentralized water and wastewater and apply it in Mexico. A key obstacle they face is that as a private water and wastewater services provider they are unable to compete with the subsidized prices of water services available to the public, even if they can deliver a higher quality and more sustainable product. A direct benefit-cost analysis for Mexico City, and potentially for other cities would likely show that a transition to high technology water and wastewater networks could rapidly become cost effective and transformative, if a apples to apples comparison of the full capital and operating costs of the systems was done. This means that either the public utilities or large system operators need to rethink their strategy, or the same subsidy has to be made available to the private water and wastewater service developer, especially to serve areas that are economically disadvantaged. This is a challenging problem in most locations, that could be solved by public-private partnerships financed by Green Bonds. Some initial experiments need to be done to understand the types of public-private business models that could be successful in terms of governance and economics, to deliver an unprecedented quality and range of service to meet the growing need of communities worldwide.

III.3. FLOOD AND DROUGHT RISK

Floods/storms and Droughts lead to significant annual average losses globally, and are projected to increase in frequency and impact. In the 20th century, the primary water sector responses to these stresses were:

- Flood control infrastructure, zoning and reservoir/dam construction
- Traditional insurance programs and catastrophe bonds.
- Drought and flood planning, early warning and response strategies.

These were typically pursued by different actors, with little integration, and the basis for risk analysis was typically the use of relatively short at site climate records to develop a statistical rating of the annual risk or probability of exceedance of a “design” event. With growing populations, changing social preferences, increasing economic activity, and changing land use and climate, the inefficiency of this traditional approach has become increasingly apparent, as impacts increase and are not effectively managed. Further, as (Bonnafous, Lall, & Siegel, 2017a, 2017b) show, a consequence of globalization is that supply chains or even a single company may experience significant flood and drought risk across their portfolio of global assets in the same year, due to the space-time clustering of climate extremes. This clustering emerges from the nature of the underlying climate variability – a combination of nearly cyclical climate patterns at global scales with preferred time scales of recurrence every 3-7 years (El Nino), 8-12 years (North Atlantic Oscillation), 16-20 years (Pacific Decadal Oscillations), 40-80 years (Atlantic Meridional Oscillation) in addition to the trends imposed by anthropogenic climate change. Thus, a company's exposure may be 3 to 10 times more than what may be expected by the traditional risk estimation process. This is very different from the random extreme event assumption made in traditional risk analyses, designs and insurance pricing. To an extent, periodic climate regimes and their impacts are predictable, and a large body of academic literature has emerged around this topic. This is getting translated into the consulting and insurance industry, as well as into water system operation (N. E. Brazil, Philippines, USA, (Asefa, Adams, & Wanakule, 2015; Clayton, Asefa, Adams, & Anderson, 2010; Sankarasubramanian, Lall, Devineni, & Espinueva, 2009; Sankarasubramanian, Lall, Souza Filho, & Sharma, 2009; Souza Filho & Lall, 2003).

III. 3.1 Potential Disruption

Financial Instruments

Gaining impetus from the dramatically increased awareness of climate induced risks, and the growing perception of climate impacts on cities (e.g., the Day zero analyses following Capetown), and the limitations of existing insurance-like instruments, a dramatic increase in creative financial instruments to address climate risks is likely. Take floods for example. Insurance companies are developing global flood risk models and integrating climate change aspects. However, most of this work does not address the potential prediction of flood risk changing cyclically over the next few years or decades, or of the local or global spatial correlation of risk. It is primarily designed to serve traditional insurance contracts (that require financial loss verification), or local zoning rules that work off a point estimate of a 100-year event (or similar). Such estimates continue to have significant uncertainty and potential for mispricing risk in the near and long term.

An alternative that has been emerging and could see widespread application is the use of parametric instruments, e.g., index insurance, or catastrophe bonds. A key aspect of such an instrument is the definition of a parameter or an index associated with the event of concern. If such an index is triggered the instrument pays off without the need for actual loss verification. The premium is priced based on the probability of event occurrence, rather than on loss. The transaction costs are consequently substantially lower, with improved pricing. Further, information on the changing/predicted risk of event occurrence can be used to update premium pricing thus sending a risk signal that could help users and markets prepare for the potential loss. An example of one of the early applications of such an idea was in Peru where the central banks were insured from floods, through a parametric index linked to the El Nino conditions (Khalil, Kwon, Lall, Miranda, & Skees, 2007; Skees, Hartell, & Murphy, 2007). Similar products have been developed and applied for drought and also to securitize water market option contracts and utility finances, including their use as ex ante or forecast insurance, that pays out potentially even before an event occurs in many different settings and countries (Brown & Carriquiry, 2007; Carriquiry & Osgood, 2012; Chantarat, Barrett, Mude, & Turvey, 2007; Goes & Skees, 2003; Zeff & Characklis, 2013) (Bjerge & Trifkovic, 2018; Maestro, Bielza, & Garrido, 2016). The Caribbean Risk Facility developed by the World Bank provides an example of a regional risk pooling and indexing approach.

Such instruments are emerging as disruptive tools for water/climate risk management for the following reasons:

- They can be offered to farmers, individuals, corporations, or nations (i.e., easily customize to scale). Donor countries/organizations, and relief programs can use such instruments to provide a mechanism for rapid emergency response in affected countries or areas, without waiting to mobilize resources to effect a response.
- They offer the opportunity to deal with financial needs when a catastrophic risk is manifest. This addresses a key bottleneck for a rapid emergency response.
- They can be designed to cover multiple types of hazards and potential losses through an appropriate choice of indices in the same contract, and hence a buyer can much more clearly evaluate what their risk exposure pathways may be and seek an instrument that provides an appropriate coverage at a lower cost. This is especially important for water markets or water futures contracts. A product like this could have allowed Capetown, Sao Paulo or Santa Barbara to have the financial resources to rapidly acquire alternate water sources or invest in technologies when their supply became constrained, if the underlying reason had been diagnosed, indexed and priced. The risk covered in this way need not just be of climatic origin. It only needs to be indexed to a risk-related parameter for which data is collected by a third party.
- Water utilities and managers are often reluctant to act on probabilistic climate forecasts, and their conservatism can lead to a loss of opportunity to mitigate risk. If the risk of using such forecasts were also indexed, then managers would be able to take such opportunities recognizing that the potentially adverse consequences

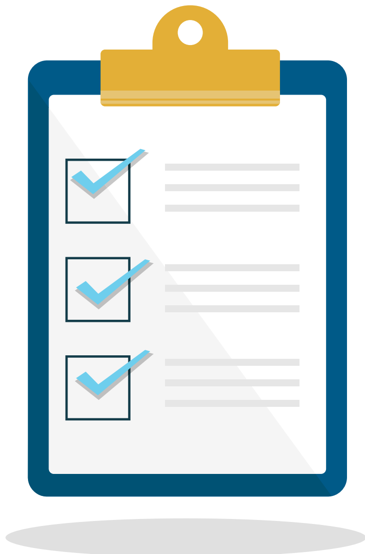
are financially covered. This can stimulate demand for the product, and also provide resilience to water operations.

- A variety of organizations, not just insurance companies, could start offering such products, if basic data on climate parameters of interest were publicly available and forecast. This has now become possible due to the interest in climate change with both public and private sector providers.

There are no apparent barriers to the development of such products, other than the ability to collect the data related to the index of interest, by a neutral third party and link it to a payment mechanism as well as a risk analysis.

III.4. RESOURCE/ ENVIRONMENTAL MANAGEMENT/ REGULATION

A well-developed set of principles for water resource management and regulation of its quantity and quality are now in place in most countries. However, their effectiveness is continually questioned. Let's take environmental regulation as an example. Companies and cities are asked to file environmental impact statements (often expensive), prior to new development. Using sparse information on baseline conditions as well as potential impacts, a discharge permit may be granted. Subsequently, there is compliance reporting, and fines if there is a violation of the permit. Separately, the regulator, or more often, a science agency may collect data on ambient water quality at a few places on the water body. Over time, the cumulative effects of pollution from multiple dischargers, and the climate induced cycles of sediment production and deposition, accompanied by



contaminant attachment, resolution, and deposition may occur, threatening the ecological function of the water body that was protected. Rarely is the monitoring and emissions data brought together to assess the reason the problems emerged and to re-allocate permits. One can visualize a corresponding example for water rights allocation based on a few years of data, and subsequent severe, sustained drought. These situations emerge as serious concerns, with media attention, and little ability to address when they are manifest. Many of the conflicts related to mining and water in S. America and elsewhere can be traced to such regulatory and allocation failures. How should one address the changing conditions in such settings?

Some of the innovations that emerged around anthropogenic climate change provide an interesting example of a potential for disruption in environmental regulation and resource allocation. First, there has been a movement towards assessment and voluntary disclosure of carbon emissions and footprints by public and private entities. Second, intensive analyses of trends in emissions, greenhouse gas concentrations, and climate impacts across many sectors emerged. Third, attribution of climate events and impacts to potential causes using causal and statistical modeling emerged. The resulting awareness of the causal chain and its impacts has started shaping the behavior of the actors responsible as well as public policy. While this process is far from complete or successful, it provides an interesting paradigm for local and regional action on water quantity and quality regulation. While climate change impacts projected for the mid to late 21st century are a significant concern, the associated uncertainties and the long time horizon contribute to the political stalemate. On the other hand, water quantity and quality are a current and emerging concern over most of the world, and this provides impetus for immediate action.

III.4.1 Potential Disruption

Data driven adaptive, participatory regulation and investment

Environmental NGOs (e.g. The Nature Conservancy, The World Wildlife Fund), their innovation partners (e.g. Techstars) and citizen scientists are increasingly active in creating data portals and analyses related to water conditions in many ecosystems, as well as in developing stakeholder participation processes to implement ecosystem or watershed services. Corporations and governments are drawn into these processes, thus influencing the overall environmental regulatory process and water allocation decisions. So far these activities have been restricted to actions in specific locations, and to specific local issues.

Given the interest in Green Bonds (Dupont, School, Levitt, & Bilmes, 2015; Shishlov & Morel, 2016), the NGO activity promoting their use, and the interest of governments in using these instruments, there is an opportunity for a radical transition in the way environmental regulation is financed and implemented. Green Bond issuers would require mechanisms and data to verify that the environmental investment objectives were met. From a watershed management perspective, this would require monitoring of emissions, mitigation actions and outcomes, followed by analyses of attribution to the instruments used. This could change the paradigm from passive regulation to active investment and management driven by environmental goals with both short and long term objectives. Modern data collection and sensing tools could significantly reduce the cost of monitoring, and also the changes in the system could potentially reduce the burden, the cost and the time and effort involved in initial permitting actions.

Since a significant convergence of players and actions is needed to enable this transition, I expect that by 2030 only a few examples may develop in areas where there is an obvious and critical need. These would be in places where there is a push by both the financial and the NGO communities, and the government is receptive. However, in the long run, enabled by data and interest, and the continuing pressure on license to operate for major global companies, and their competition for water and land, disruption of the water sector in this direction will take place.

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IV. The Future of Water is Digital

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IV.1 INTRODUCTION

Our relationship with water is undergoing a transformation in response to increased demand for water (e.g., human consumption, energy and food production, etc.), the impacts of climate change and poor water quality.

Digital technologies (e.g., information communication technologies or ICT) are leading the transformation through the emergence of technologies such as remote sensing, inexpensive sensors, smart devices (e.g., internet of things), machine learning, artificial intelligence, virtual reality, augmented reality and blockchain. This digital transformation of water is currently enabling real time water quantity and quality monitoring, vastly improved management of infrastructure assets, direct consumer engagement and facilitating the adoption of off-grid and localized infrastructure technologies (e.g., air moisture capture, neighborhood scale treatment systems, etc.). Not only will water utilities be transformed by digital technologies but the public sector will benefit through improved knowledge of water supply, demand and quality to better inform public policy and investments. The private sector will be positioned to ensure the efficient and effective use of water in their supply chains, operations, and with products (e.g., water efficient personal care products, washing machines, etc.).

Several organizations have already acknowledged the potential of digital water technologies. The World Economic Forum frames the adoption of digital technologies in all industrial sectors as the Fourth Industrial Revolution or 4IR and the digital transformation of water is part of this revolution,[1] the water utility sector is framing the "digital utility"[2] and the Aspen Institute and Duke University framed the "Internet of Water."[3]

Digital technologies have the potential to democratize access to water data, actionable information and, in turn, to safe drinking water. Achieving SDG 6 may be within reach through digital technologies and their ability to facilitate the adoption of other innovative water technologies. By 2030 we will see digital water technologies as commonplace just as we have seen digital technologies become integrated into the energy (e.g., Nest) and transportation sectors (e.g., Uber and Lyft). Moreover, digital technologies will enable leapfrogging of traditional infrastructure (e.g., centralized systems) to hybrid (e.g., centralized and decentralized) and new systems (e.g., off-grid) by providing real time access to water quantity and quality data for consumers, technology providers and regulators.

IV.2 WHY DIGITAL?

Currently, approximately 4 billion people live in water-scarce and water-stressed regions, with nearly 1 billion people without access to safe drinking water and almost 1 million deaths per year from waterborne diseases. The World Economic Forum projects that, under business-as-usual policy and technology practices, the world faces a 40 percent gap between water supply and demand by 2030. In addition to water scarcity impacts, the world also faces negative effects from flooding and poor water quality to economic growth, business continuity, ecosystem health and social well-being.

In particular, cities are vulnerable to the impacts of water scarcity and extreme weather events. These impacts are currently being realized in many global cities and, as a result, cities are looking to increase their resiliency to changing hydrologic conditions. Research by CDP Water highlights the response of global cities to these water risks.[4] This research indicates the cities most concerned about their water supply are in Asia and Oceania (84 percent), with serious risks also identified in Africa (80 percent) and Latin America (75 percent). One hundred ninety-six cities reported risks of water stress and scarcity, 132 a risk of declining water quality, and 103 a risk of flooding.

1 Sarni et al., 2018.
2 Karmous-Edwards, and Sarni, 2018.
3 The Aspen Institute, 2017.
4 CDP, 2017.

Another recent study analyzed 70 surface water supplied cities with populations exceeding 750,000.[5] The results indicate that, "in 2010, 36 percent of large cities are vulnerable as they compete for water with agricultural users. By 2040, without additional measures, 44 percent of cities are vulnerable due to increased agricultural and urban demands.

Impacts from water scarcity on a regional and national scale were also evaluated and presented in a 2016 report from the World Bank, indicating that that: "water scarcity, exacerbated by climate change, could cost some regions up to 6 percent of their GDP, spur migration, and spark conflict and the combined effects of growing populations, rising incomes, and expanding cities will see demand for water rising exponentially, while supply becomes more erratic and uncertain."[6]

Current public policies and infrastructure will not be sufficient to keep pace with needs from an increasing global population. The global population *is currently* increasing by approximately 70 million people each year. As a result, the total global population is projected to reach 9.6 billion by the year 2050.[7] The International Union for Conservation of Nature (IUCN) estimates that by 2050, demands for water, energy, and food will increase by 55, 80, and 60 percent, respectively.[8]

Digital technologies will be transformational in positioning the water industry, other commercial sectors and governments for expanded resilience from increased demand for water and the impacts of climate change (e.g., loss of stationarity and extreme weather events). The water industry has the opportunity to take the lead in addressing 21st century water risks through the adoption of digital water technologies.[9]

IV.2.1 DIGITAL WATER ROADMAP

As is the case with so much of modern life, the global water sector is adapting to the information age and data-driven innovations. Disruption in the coming decade will be delivered by digital water technologies that allow for the decentralization of large, traditional water utilities and the incorporation of smaller, remote systems. Similarly, innovations in water collection and distribution would foster a new generation of blended or hybrid utilities to diversify the means by which drinking water is collected (e.g. rain collection, air moisture capture, etc.) and wastewater is treated (e.g. natural treatment systems).

5 Padowski and Gorelick, 2014.
6 The World Bank, 2016.
7 Sarni, 2015.
8 International Union for Conservation of Nature, 2013.
9 Sarni et al., 2018.

The global water sector can look to other industries for reasons to embrace digital technologies such as energy and transportation. First, harnessing digital technologies will allow water utilities to shift their focusses from the paradigmatic economies of scale to those of economies of efficiency. Second, moving from a system of large, stand-alone water resources to one of dynamically integrated micro-systems affords an entirely new level of resource allocation and utilization. And third, introducing new incentives, payment systems, and engagement initiatives would transform the interface between utility and customer and in turn create a new generation of engaged water consumers.

Additionally, digital innovation in this sector would foster an environment in which water is no longer managed in an insular manner, but rather a collaborative one together with other resources, particularly in the energy sectors.

IV.3 DIGITAL WATER TECHNOLOGIES

An overview of several digital water technologies transforming water are summarized below.

IV.3.1 Watershed and Consumer Connectivity

Surface and groundwater data within watersheds can now be collected and shared at the local, regional, and even global scales. The digital technology toolkit now includes satellite imagery for surface and groundwater evaluation and flood forecasting. Drones can also be deployed to assess real-time conditions upstream as a preventative measure and not merely for periodic planning as extant protocol usually dictates. Just as blockchain applications have been used to increase the transparency of supply chains in other sectors, they could potentially be employed to generate permanent, collective record-keeping of water use and transactions for a range of stakeholders.

There is now the ability to acquire water data at the global, regional, watershed, and local scale to provide a vastly improved understanding of surface and groundwater supplies. Data acquisition and analytics technologies that address these needs include satellite imagery and analytics for groundwater resource evaluation (e.g., NASA GRACE) and for

> Blockchain applications also have the potential for collective record-keeping of water quantity and quality data, allowing multiple groups of stakeholders to create an immutable record of data

flood predictions (e.g., Cloud to Street). In addition, there is demand for national-scale water data acquisition and management (e.g., AKVO Foundation) to track progress against Sustainable Development Goal 6 (universal access to safe drinking water), inform public policies (e.g., California Sustainable Groundwater Management Act), develop watershed scale monitoring of hydrologic conditions (University of Berkeley California Hydrologic Monitoring), and tackle global water challenges (e.g., Earth Genome Project).

Connectivity also includes the use of remote sensing. For example, in Crete and Sardinia, satellite data are being used to improve upstream water-quality monitoring.[10] These types of data provide water utilities the ability to monitor natural systems on a real-time basis. In general, water utilities use hydraulic models for planning and expanding purposes only once every few years.

Blockchain applications also have the potential for collective record-keeping of water quantity and quality data, allowing multiple groups of stakeholders to create an immutable record of data collected by each and allowing open access to that data by all parties. Blockchains, which are already at work in making transparent supply chains, could be used in the water sector to improve mapping of tap-water quality.[11]

Digital water technology solutions will also change the relationship water utilities have with customers as society increasingly embraces digital technologies in all aspects of their lives (e.g., mobility, communication, and entertainment) and it is reasonable to conclude service providers such as water utilities will now be part of the mix. With new efforts toward sustainability and water conservation efforts, water utility companies are beginning to establish innovative strategies to help engage consumers and restructure the way people think about water use.

10 International Water Association, 2018.
11 Weisbord, 2018.

Companies and products such as Rachio, HydroPoint, Dropcountr, and WaterSmart utilize digital technology to promote sustainable water use and allow customers to access utility data and information with ease. Dropcountr and WaterSmart use digital technology to create reports using real-time monitoring from smart sensors to deliver data to customers. Rachio utilizes smart sensing technology, monitoring devices that essentially operate with an on/off switch and can use weather patterns to conserve water.[12] The company also offers smart irrigation and sprinkler-control functions that are user-friendly, easy to install, and compatible with already existing at-home watering systems. HydroPoint allows customers to save both water and money through smart irrigation, leak and flow monitoring, and professional services.[13]

Companies that take advantage of these developments in customer service are benefiting. With new digital technologies such as AI chatbots, customers can ask questions and get answers whenever they want, opening vast possibilities for consumer engagement, providing customer alerts, and also water consumption and conservation information. Utility companies that embrace these technologies are improving their customer service and meeting the high demands of consumers.

IV.3.2 Asset Management

The most obvious opportunity for digital water technology adoption is in asset management and the ability to monitor water utility infrastructure performance in real time.[14] Digital water technologies can vastly improve the efficiency and effectiveness of infrastructure repair and capital investments. Utilities now have the opportunity to have every asset recorded within their GIS system with structured and unstructured data from across all departments for actionable insights to decrease costs and risks (e.g., Redeye). Today, most hardware companies (e.g., pump manufacturers) also provide software services as part of the product enriched with data analytics for insights, optimization, and future automation. The integration of critical data across utility departments, such as the finance department, work order systems, GIS system, and SCADA, will provide more accurate predictive asset management and an extension of asset life. Utilities will also be able to couple data with VR and AR tools for asset assessment and preventative maintenance (e.g., Fujitsu). In addition, utilities can utilize satellite imaging for cost-effective leak detection, (e.g., Utilis) and wastewater utilities can use smart remote sensing products to provide early detection and prediction on wastewater conditions (e.g., Kando). Asset management now also includes AI applications to manage infrastructure assets. There are several data-analytical companies armed with data scientist and application developers focusing on the water sector (e.g., EMAGIN).

12 Rachio, 2018.
13 HydroPoint, 2018.
14 Karmous-Edwards, and Sarni, 2018.

Several utilities are also moving towards adopting "digital twin" applications, a pairing of the virtual and physical worlds that allows analysis of data and monitoring of systems to avoid problems before they even occur, prevent downtime, develop new opportunities and plan for the future by using simulations.[15] The digital twin approach uses sensors to gather data about real-time statuses, working conditions, or positions that are integrated with a physical item. Digital twin applications allow lessons to be learned and opportunities to be identified within a virtual environment, which can be applied to the physical world—ultimately transforming asset management and operations.

Other benefits to digital solutions for the water utility sector include the ability to monitor water quality on a real-time basis at the tap or within the environment. Digital technologies allow citizen scientists to collect real-time water data with low-cost sensors (e.g., the US Environmental Protection Agency and the state of Georgia), open-source data platforms (e.g., California Open and Transparent Water Data Platform), smart residential irrigation and water management systems (e.g., Rachio), water quality testing at the tap (e.g., Microlyze), and blockchain applications to promote transparency and facilitate transactions (e.g., Power Ledger).

There is also the potential for digital technologies to facilitate the use of off-grid and localized solutions for water and wastewater treatment, along with strategies to build hybrid decentralized-centralized systems. Real-time water system performance and water quantity and quality monitoring are currently facilitating the adoption of off-grid air moisture water generation (e.g., Zero Mass Water) and localized treatment technologies (e.g., Organica). Digital technologies facilitate the adoption of off-grid and decentralized technologies by eliminating or reducing the need for centralized testing and reporting. Real time monitoring allows infrastructure technologies to become independent and more directly connected to the needs of the customer and consumer.

15 Marr, 2017.

IV.4 A DIGITAL WORKFORCE

The development of digital technologies now requires the water utility workforce to adapt and learn new skills in order to keep up with the pace of evolution within the global economy and systems of commerce. In addition to recruiting new talent proficient in information technology, companies need to train existing employees and attempt to continue to operate and adjust to new systems seamlessly.

Another way to frame the digital workforce is how the "no-collar" workforce will be incorporated into company operations.[16] In this scenario, robotics and artificial intelligence (AI) will likely not displace the majority of workers. Instead these digital tools offer opportunities to automate some repetitive, low-level tasks. More importantly, intelligent automation solutions may be able to augment human performance by automating certain parts of a task, thus freeing individuals to focus on more human-necessary aspects, ones that require empathic problem-solving abilities, social skills, and emotional intelligence.

Digital technologies can enable water utilities to collaborate with utilities in different states to identify solutions to infrastructure problems. For example, the White House Utility District (WHUD), which serves approximately 90,000 consumers and businesses in northern Tennessee, saved more than $20 million by identifying leaks in their infrastructure system with digital technologies.[17] WHUD collaborated with data collected from the California Public Utilities Commission to determine leakage costs with comprehensive data analysis and comparisons of the regions.[18]

VR and AR applications can also benefit the water utility workforce by reducing risk and saving in maintenance costs, engineering tests, and innovation, and allow users to test or simulate real-world situations without the usual dangers or

16 Abbatiello et al., 2017.
17 Kanellos, 2017.
18 Ibid.

costs associated with large engineering projects. With VR, asset maintenance professionals can immerse themselves to fully and accurately experience what a situation would be like in real life. VR also allows the identification of design flaws or other potential problems with efficiency, which can then be solved before any problems actually occur.

IV.5 CHALLENGES

While the digital water technology toolkit offer considerable promise, there are challenges in scaling adoption of these technologies at scale. Two of the challenges are highlighted below.

IV.5.1 Workforce capacity and training

Whether, real or perceived the water sector and users are slow to adopt new technologies due to; a lack of incentives, risks from adoption and siloes of data owners/departments. As a result, proven technologies are strongly favored over unproven or emerging technologies. However, there are now strategies to de-risk new technologies by water technology hubs and accelerators working closely with utilities (e.g., Imagine H2O, Water Start, and Current). In general, water workforces are not trained in digital technology solutions and workforce transformation will be necessary to scale the adoption of digital technologies.19 A Harvard Business Review article offers valuable insight on the workforce challenge in adopting water data technologies: "Using and interpreting data is not only a search for insights; it's also about enlisting the hearts and minds of the people who must act on those insights."[20]

V.5.2 Cybersecurity

Because utilities are critical infrastructure, cybersecurity is a high priority, and often one reason utilities insist on not using cloud-based solutions and requiring on-premise solutions instead. Utilities need to constantly strengthen their operations with innovative cybersecurity solutions as well (e.g., Siga, and Radflow). The water utility sector is not alone in having to keep pace with the ever-increasing assault on public- and private-sector enterprises in the form of data theft and business disruption.

In 2015, the US Department of Homeland Security responded to 25 cybersecurity incidents in the water sector (8.5 percent of the total incidents reported) which marked a nearly 80 percent increase in water-sector incidents over the previous year.[21]

19 Krause et al., 2018.
20 Cespedes and Peleg, 2017.
21 Clark et al., 2017.

IV.6 ACCELERATORS

While challenges remain, there are new tools to accelerate the adoption of digital water technologies. For example, new business service models such as pumps as a service, operations as a service, and platforms as a service—are emerging in other sectors and are slowly having an impact in the water sector (e.g., Grundfos Cloud-connected pumps). Also, there are large volumes of water data collected by utilities from video, satellite images, social media sources. As a result, water utilities need the capacity to process these data for more informed decision making.

We can also not underestimate the impact of a digitally savvy workforce and consumers. Digital solutions are prevalent in the retail, transportation, and energy sectors, which has raised the expectations of workers and consumers that other aspects of their lives will be "digitally enabled." The water sector is no exception to this trend. Also, entrepreneurs outside the water sector are now engaged and motivated to bring new ideas to solving water challenges. In many cases the solutions are focused on digital technologies. These entrepreneurs are being brought into the water sector by organizations such as; Imagine H2O, Current, WaterStart, 101010, The Nature Conservancy/Techstars partnership and ABInBev/ZX Ventures.

IV.7 CONCLUSIONS

In developed economies, access to water has been taken for granted and this acquiescence manifests itself first and foremost in a lack of transparency. Customers almost never think about their water supply until there is a problem, and this in turns sends a message to their providers that transparency is neither a priority nor even expected. Modernized, developed society is disconnected from the idea that water is a valuable and strategic resource to be monitored and managed. Instead, their perception of water is dissociative, thinking of water in the contexts of its different manifestations (i.e. drinking water, gray water, storm water). In the future, these perceptions need to coalesce into a singular view of a singular resource and the best way to achieve that is through transparency between the utility and the customer.

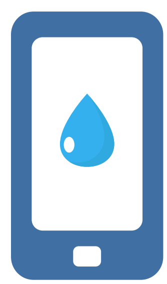
Transparency at this level is most quickly achieved through customer engagement and education. This means sharing information about water supplies that is not always favorable, like supply shortfalls and quality issues, topics that utilities have long been hesitant to share. Digitizing data collection and employing open exchanges of information will both engage and inform water customers, which will in turn foster a new culture of transparency.

Innovations in technology, most particularly on the digital front, have made rapid changes in the energy sector like the adoption of renewables and the trend toward micro-grids. The water sector would reap substantial benefits by taking pages from these play books. Blending or hybridizing water utilities by incorporating the positive attributes of large, centralized water systems with those of off-grid, localized systems would power the optimization of water management and yield reliable, equitable distribution. An additional benefit hybridization offers is redundancy, the reliance on multiple smaller resources that can be reconfigured to accommodate repairs and renovations, emergency protocol, and even quarantines.

The catalysts necessary to bring about next generation water practices are in many ways cultural changes—increased expectations of transparency and the education of water customers and policy makers. One example is the rise of innovative business models that permit and even encourage technology ventures to share the risks of rolling out new technologies with their utility partners. Expanding on the trend of providing "Anything as a Service" (XaaS) that is perhaps most familiar in the cellular communications arena (e.g. smart phones as a service), technological advances in hardware become advances in services (e.g. pumps as a service, sensors as a service).

Generational change is another, extremely powerful enabling force because new, more sophisticated customers already expect digital solutions to so many other areas of their lives from personal communications and social media, to transportation (e.g. congestion pricing) and even their dwellings (e.g. Nest thermostats). The emergence of a no-caller workforce is made up of individuals with expectations of "digital instantaneity," people who demand real-time information and solutions and possess an affinity for self-service.

More than anything, efforts on these fronts will power continued innovation that will in turn drive modern regulation. Ultimately, this means reinventing how water is shared and 205 Strafford Avenue Wayne, PA delivered, without losing sight of the overarching goal—a safe, reliable water supply accessible by all.



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