Progress and Promise Transitioning to the One Water/Resource Recovery Integrated Urban Water Management Systems

Glen T. Daigger, Ph.D., P.E., NAE, Dist.M.ASCE[1]; Sybil Sharvelle, Ph.D., M.ASCE[2];
Mazdak Arabi, Ph.D., M.ASCE[3]; and Nancy G. Love, Ph.D., P.E., M.ASCE[4]

Abstract: Changing circumstances and the availability of new technologies are causing urban water systems to transition from managing system components in a separate and linear fashion to an integrated "One Water" approach that focuses much more on recovering resources, including water, energy, nutrients, and other materials. These systems often include both distributed and centralized components and are referred to as hybrid systems. The components of these integrated One Water and resource recovery systems are described, along with the benefits that they provide. Enabling factors, along with impediments, are described, including new technologies, the need to balance human services and environmental needs, the continuing evolution of optimal system configurations, concerns created by new and emerging issues, and the need to adapt existing institutions and practices. The literature reviewed illustrates the growing research interest in these topics, along with progress translating these approaches into practice. **DOI: 10.1061/(ASCE)EE.1943-7870.0001552.** *© 2019 American Society of Civil Engineers.*

Author keywords: One Water; Resource recovery; Urban water; Hybrid systems; Transitions.

Introduction

After more than a century of water management in an urban context in a separate and linear fashion, a transition to a much more integrated approach is occurring. This approach is based on the concepts of "One Water" and resource recovery and based on the use of hybrid distributed and centralized system components. This transition responds to changing circumstances and anticipates not only current but future needs and realities as well. This paper addresses the changing context for urban water management and the key elements of the evolving One Water and resource recovery approaches. The integrated hybrid distributed and centralized systems required to fully implement these new systems are then described. Numerous factors must be successfully addressed to implement these new systems, and they are addressed under the heading of enablers and impediments. The body of literature reviewed illustrates the growing research interest in these topics and the transitions in professional practice that are enabling their practical implementation.

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 in the 19th and early 20th centuries (Sedlak 2014; Schneider 2011). The spread of waterborne diseases (e.g., cholera, typhoid) in urban areas caused by pollution of local water supplies led to the 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 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 the development of drinking water treatment, and environmental degradation caused by pollution discharges led to the development of used water (often called wastewater) treatment.

Due to economies of scale for the 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 have been occurring in the 21st century, as described in what follows. The large-scale and centralized nature of current urban water management systems generally minimizes capital investment for the supporting infrastructure through economies of scale for facility construction, but often at the expense of efficient resource use. For example, 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 (Kavvada et al. 2018;

---

[1] Professor of Engineering Practice, Dept. of Civil and Environmental Engineering, Univ. of Michigan, Ann Arbor, MI 48109 (corresponding author). Email: glendaigger@comcast.net

[2] Associate Professor, Dept. of Civil and Environmental Engineering, Colorado State Univ., Fort Collins, CO 80521.

[3] Borland Chair of Water Resources, Professor of Dept. of Civil and Environmental Engineering, and Director of One Water Solutions Institute, Colorado State Univ., Fort Collins, CO 80521.

[4] Borchardt and Glysson Collegiate Professor, Dept. of Civil and Environmental Engineering, Univ. of Michigan, Ann Arbor, MI 48109.

Note. This manuscript was submitted on October 15, 2018; approved on December 27, 2018; published online on July 24, 2019. Discussion period open until December 24, 2019; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Environmental Engineering***, © ASCE, ISSN 0733-9372.

J. Environ. Eng., 2019, 145(10): 04019061

Table 1. Comparison of historic and future approach to urban water management

Item	Historic (19th and early 20th centuries)	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

Bradshaw and Luthy 2017). Even while economies of scale exist for treatment systems, the energy requirements for treatment can be outweighed by energy savings from the conveyance of treated water (Kavvada et al. 2018). Further, combining various components of the used water stream for joint transport reduces resource recovery opportunities, as discussed in what follows.

While many factors were responsible for the adoption of the centralized approach to urban water systems during the 19th and early 20th centuries, two of the most important were the general availability of water and other resources, relative to demand, and the general lack of treatment technologies and monitoring and autonomous control capabilities. The human global population grew from one billion at the beginning of the 19th century to two billion in the first quarter of the 20th century (Wikipedia 2018), compared to the current global population of over seven billion (UN 2017). Economic growth, which is the true determinant of water demand, has grown much faster. Moreover, urban populations have grown from around 20% to more than 50% of the total (UN 2018). Thus, while water and other resources were generally available in the 19th and early 20th centuries, this is no longer the case (Hoekstra and Wiedmann 2014; Hoekstra and Mekonnen 2012). Today, available sustainable water resources are generally fully allocated, and in many regions of the world they are overallocated (UN 2012). The general lack of technologies in the 19th and early 20th centuries for reliably and cost-effectively treating contaminated water led 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 convert relatively contaminated water to potable, and even higher, quality standards, and continuous monitoring technology coupled with autonomous control ensures the consistent delivery of safe water. Thus, the main factors that resulted in the development of the current urban water management system no longer exist.

Development of One Water and Resource Recovery Systems

Today the world faces increased resource scarcity (water and other resources) compared to the 19th and early 20th centuries when the current urban water management system evolved (Steffen et al. 2015; Rockström et al. 2009). Water resource scarcity is further exacerbated by climate change, which is depleting renewable freshwater resources (Huang et al. 2016). Thus, it has become necessary to implement systems that use available freshwater 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; Grant et al. 2012; Daigger 2012a, b, 2010, 2009, 2007). Table 1 contrasts some of the essential features of the historical approach to urban water management with systems evolving to meet current and future needs. The evolving systems are integrated and multipurpose in nature and rely much more heavily on local versus 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 of which they are a major component and, hence, require significant institutional and financial changes (IWA 2016a). They are also increasingly 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 exist internationally.

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.

One Water

The One Water approach to urban water management is based on the premise that all forms of water in urban areas (rainwater, groundwater, surface water, drinking water, used water, fit-for-purpose reuse water) are linked and form a system that provides the most effective service when managed in an integrated fashion (Zodrow et al. 2017; Larsen et al. 2016; Hering et al. 2013; Daigger 2012a, b, 2010, 2009). It further recognizes that the urban water cycle is connected to the broader environment, especially the watershed where the urban area is located. To provide effective service, any water management system must address not only typical hydrologic conditions, but also extreme conditions of drought and flooding. For conventional water management systems, this range of conditions is addressed by single-purpose solutions, for example, storage (dams), to address drought. This range of conditions is addressed by the One Water approach using a portfolio approach consisting of a combination of options, each one performing well in various scenarios so that the combined system is resilient over a wide range of conditions. The portfolio components of water supply include surface and ground water, conservation, roof runoff and stormwater harvesting, water reclamation and reuse, and (as a last resort) brackish and seawater desalination. Likewise, the portfolio components relating to excessive water (storms, potentially leading to flooding) consist of conventional stormwater systems (including storage, piped conveyance, and physical flood protection, such as dikes), natural systems that capture and infiltrate water (green infrastructure), and the design of the urban form to accommodate facilities like parks, for example, which can flood and be returned to service quickly and with minimal damage.

Specific system components and their relative sizes are determined by local conditions.

Resource Recovery

Application of the One Water approach is leading to urban water management systems that use existing water supplies much more efficiently. Other resources present in the urban water cycle can also be harvested, including energy, nutrients, and other materials (IWA 2016c; Wang et al. 2015; Grant et al. 2012; Daigger 2012a, 2009; Trimmer et al. 2017). Forms of energy include kinetic (the energy of flowing water), thermal, and chemical (such as the organic matter present in used water). The use of flowing water to generate electricity through hydropower systems is a familiar practice. Thermal energy can be recovered from or discharged to water using heat exchangers and heat pumps. This practice can be particularly advantageous when wastewater is collected on the building scale, where less heat is lost compared to centralized collection systems (McNabola and Shields 2013; Meggers and Leibundgut 2011). 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 (Schopf et al. 2018). The biogas can be used subsequently for a variety of purposes, such as in combined heat and power (CHP) systems, or upgraded to natural gas quality. Nutrients are recovered when biosolid products are produced for agricultural use, and phosphorus is already being recovered as the slow-release fertilizer product struvite (magnesium ammonium phosphate). Approaches to harvesting other forms of carbon, nitrogen, and rare earth metals are also being investigated (IWA 2016c). Recovery and use of these resources can provide financial and strategic advantages to urban water utilities, along with broader life cycle advantages owing to a reduced need to extract these resources from the environment (Xue et al. 2016; Fang et al. 2016). Financial advantages result, both from the revenue generated by the recovered resources and 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), which are not perceived as being useful to society. The production of usable products can increase public support for these necessary activities, in contrast to the disposal of materials, which is often thought to be wasteful and undesirable.

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. 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 and monitoring and control technologies (addressed in what follows) allow source waters of various qualities (surface, ground, rain, and used) to be treated to meet the fit-for-purpose quality requirements associated with various uses. 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 nonpotable use. 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 gray, black, and yellow water) is also an emerging trend that can provide benefits from the perspective of both resource efficiency and recovery (Daigger 2012b).

Fig. 1 provides an illustration of such an integrated system incorporating many of the centralized and distributed components described previously. Both potable and nonpotable water supplies are provided to municipal, commercial, and industrial customers. This example illustrates these water supplies being provided by local nonpotable and potable water aquifers. Water supplies are supplemented, either directly or by supplementing the nonpotable aquifer with runoff harvesting, stormwater infiltration, and wastewater reclamation (largely from graywater). Blackwater and yellow water are collected separately for resource recovery. Heat is recovered from the used water stream and the nonpotable aquifer. Salts added through water use are concentrated in a saline water stream that is exported to a saline water aquifer. While not all components in this illustration will be included in all systems, the concept is demonstrated.

Impacts of Implementing One Water/Resource Recovery Approaches

While the One Water/resource recovery approach to urban water management offers an array of advantages compared to the historical approach, many approaches can be summarized under the category of significantly improved system resilience. The distributed nature of such systems reduces reliance on single, large system components that can fail for a variety of reasons and replaces some of them with more distributed components, backed up by a centralized backbone. Thus, a failure of one system component still leaves a functioning system in place, even though the level of service may be temporarily diminished. Environmental resilience is increased both through improved system performance resilience and because the potential for reducing net resource consumption is achieved by enabling greater resource recovery. Greater financial resilience results because the large number of small system components affords more flexibility in system implementation. Greater economic resilience results because the urban water system can become a more integral component of the developing circular economy. These systems can also accelerate achievement of sustainable development goals for water (UN 2015) by providing the means to accelerate the extension of improved water service.

Enablers and Impediments

While the benefits of integrated One Water/resource recovery systems are apparent, several factors can serve to enable their implementation and can also be impediments.

New Technologies

New technologies are certainly enablers of integrated One Water/resource recovery systems. New treatment technologies, such as advanced oxidation, membrane systems, membrane bioreactors (MBRs), and ultraviolet (UV) technology have been instrumental in the implementation of integrated One Water/resource recovery systems to date (Mathon et al. 2017; Sun et al. 2017; Zodrow et al. 2017; Knopp et al. 2016; Moreira et al. 2016; Zietschmann et al. 2016; Logan and Elimelech 2012; Logan and Rabaey 2012; Judd and Judd 2011). These technologies achieve highly effective and reliable treatment, and, because unit treatment costs decrease rapidly with capacity and plateau at lower capacities than more

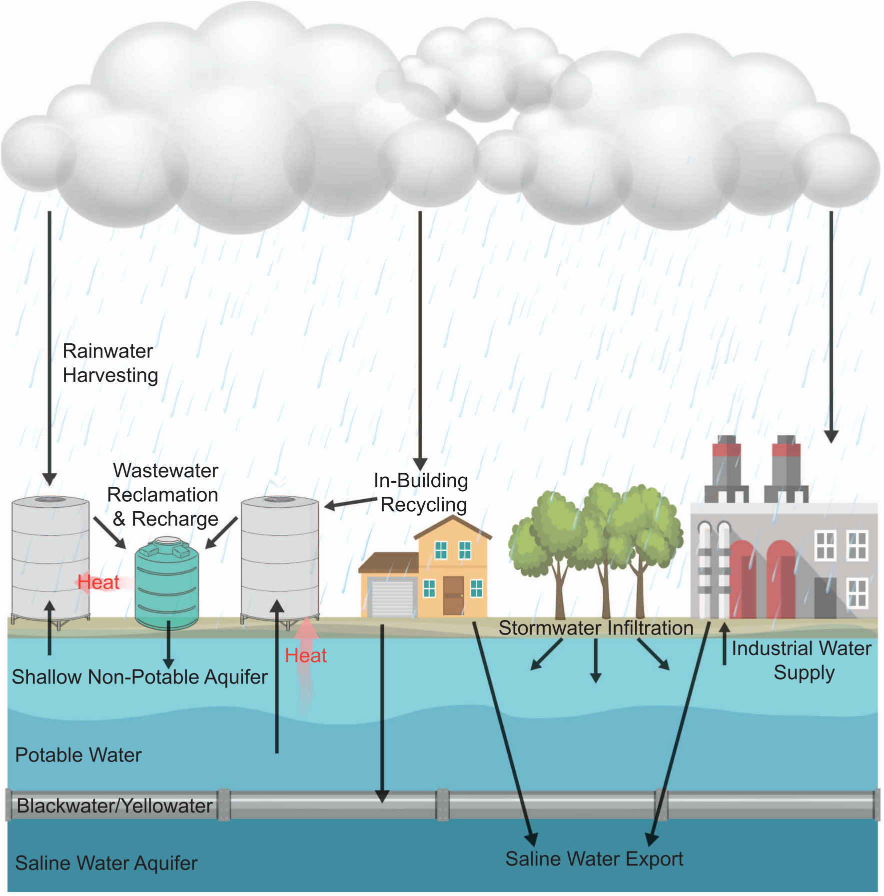

Fig. 1. (Color) Example integrated One Water/resource recovery hybrid centralized and distributed urban water management system.

conventional technologies, they allow cost-efficient application in the smaller installations required for distributed systems (Liang et al. 2018; Gassie and Engelhardt 2017). Anaerobic treatment technologies are already widely used in the treatment of high-strength industrial wastes and organic sludges resulting from used-water treatment, thereby resulting in the conversion of biodegradable organic matter into biogas. Research is ongoing on the development of technologies, such as anaerobic MBRs (AnMBR) for the treatment of low-strength wastewater (Chen et al. 2017; Bair et al. 2015). Thermal hydrolysis (THP) has emerged as an enabling technology to significantly enhance the performance of downstream anaerobic treatment technologies for municipal used-water organic sludge treatment and other organic materials, leading to increased conversion of organic matter into biogas for energy recovery and production (Yousefifar et al. 2017; Barber 2016). The recovery of phosphorus from the used-water cycle through struvite (magnesium ammonium phosphate) precipitation is an emerging technology, already with a significant number of technically and commercially successful applications (Ward et al. 2018; Nättorp et al. 2017). Other nutrient removal technologies are also developing (Brewster et al. 2016). Rapid advances are occurring in biological treatment technologies, partially enabled by the rapid deployment of molecular biology. Nanotechnology and the development of new materials offer further and as yet untapped possibilities (Zodrow 2017).

Technologies used for continuous monitoring of water quality coupled with autonomous control of treatment system operations have served as important enablers for decentralized systems that supply nonpotable water locally. Such technology has increased in reliability while also decreasing in price as it has gained popularity (Qin et al. 2016; Bonastre et al. 2005). Guidance for decentralized systems for nonpotable water supply recommends that grab sampling for fecal indicator organism be replaced by continuous monitoring of surrogate parameters that correlate with pathogen reduction in unit processes (Sharvelle et al. 2017). Inline monitors should be linked with autonomous control systems. This approach offers the capability to ensure that safe water is reliably supplied to end users while also reducing the cost and time burden associated with periodic sampling of fecal indicator organisms. Continued improvements in sensor technologies, the growing ubiquity of cyber systems, advances in data mining and artificial intelligence, and increased understanding and application of complex system theory will all be important system-wide enablers of decentralized technologies and the One Water approach (Kerkez et al. 2016).

At the same time, advances are needed in the conveyance of water and associated urban water cycle constituents. Increasing water conservation can increase water age in water distribution systems, which adversely impacts water quality, and lower flows of much more concentrated used water in collection systems is leading to solids deposition and increased corrosion (Penn et al. 2017). Source separation results in process streams with very different characteristics compared with traditional sewage (Hodgson et al. 2018). The concentration of solids in blackwater significantly exceeds levels traditionally experienced in domestic sewage, compromising the use of conventional sewer design criteria for systems to convey it. There are also potential impacts to treatment process efficiency (McKenna et al. 2018). Scaling is an important issue for yellow water conveyance, along with provisions to either minimize ammonia production through urea hydrolysis or minimize gaseous emissions if significant urea hydrolysis for forming ammonia occurs (Fewless et al. 2011). Experience gained with fecal sludge transport may contribute important knowledge and experience to assist with the redesign of the conveyance component of urban water management systems.

The integrated systems described possess all of the characteristics of complex, techno-socio-economic systems. Continued improvements in sensor technologies, the growing ubiquity of cyber systems, advances in data mining and artificial intelligence, and increasing understanding and application of complex system theory will all be important system-wide enablers (Kerkez et al. 2016).

Balancing Human Services and Environmental Needs

Balancing human services and environmental needs serves as an impediment with at least two dimensions: (1) providing acceptable levels of service across the varied socioeconomic strata of society and (2) engendering conflicts and trade-offs between providing services to humans and preserving the environment.

The first dimension can be framed simply as uniformly achieving the human right to water and sanitation, as adopted by the United Nations in 2010 (ADD REF). Formal adoption represents, not only a commitment, but a requirement that applies to both developing and developed countries. It is enforceable internationally through well-established laws and legal precedents (de Albuquerque 2014). When many people learn of the existence of the human right to water and sanitation, they believe that water and sanitation services should be free. This is not true. Rights have responsibilities associated with them—individuals have the right to these services but also the responsibility to support the means for them to be provided. An understanding of the relative responsibilities of various actors is critical to understanding how the human right to water and sanitation is satisfied (IWA 2016d). The responsibilities of various actors may be summarized as follows:

- Government has a principal role to establish an enabling environment to allow receipt of the right that is to be satisfied. This involves the creation of regulations and regulatory bodies governing service quality, the allocation of costs, and environmental quality, along with the legal and institutional frameworks for service providers.
- Service providers, which can be public or private, have a responsibility to function within the established functional framework and make best efforts to provide acceptable service within the operating constraints inherent in the established system.
- Individuals have a responsibility to support the established service providers, including exercising responsibility in receiving the provided service and paying established fees.

The responsibilities of government and the service provider go beyond simply providing a sufficient quantity of safe water and access to appropriate sanitation facilities. The services provided must be acceptable, accessible, and affordable. The method(s) of service provision must be equitable and ensure nondiscrimination. The service provider must be accountable to the population served and use participatory processes to furnish information that is transparent, and service provision must be sustainable. While it may not be possible to fully satisfy all of these requirements at the present time, progress must be made toward them—a concept referred to as progressive realization.

Many in the developed world may hold that respecting the human right to water and sanitation applies largely to the developing world. This view ignores the notion that the human right applies to all, and issues such as affordability, participation, transparency, and achieving financial sustainability (consider the growing liability of aging infrastructure) represent deficiencies for developed-country water utilities. Fully achieving the human right to water and sanitation represents an ongoing challenge in both the developing and developed worlds.

Meeting human needs for water service is negatively impacting the natural world, as discussed previously. Indeed, as humans enter the Anthropocene, they must increasingly decide what type of "natural" world (the world outside our habitats and normal locations for human activity) they want (Daigger et al. 2017). Water management significantly affects this natural world by altering water flows through the environment (streamflow, groundwater) (Hodgson et al. 2018) and through the discharge of substances to the environment (e.g., organics, nutrients, and toxics) (Brüchner et al. 2018; Magdaleno 2018; Tran et al. 2018; Zhang et al. 2018; Roehrdanz et al. 2017; Sinha et al. 2017; Lürling et al. 2016; Vo et al. 2014). The natural environment, and the ability to provide water services to humans, is also significantly impacted by broader environmental issues, such as climate change and declining resource availability (Steffen 2015; Rockström 2009). This combination of factors calls for the development and rapid implementation of approaches to urban water management that use resources (including water, but also energy, nutrients, and materials) much more efficiently and with greatly reduced environmental impacts, while also meeting human needs, as discussed earlier.

Developing Optimum System Configurations

New system configurations, such as hybrid distributed and centralized systems incorporating fit-for-purpose water production and use and separately collecting and treating individual used water streams (source separation), offer the potential to realize the improved system performance identified earlier. 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 (Wielemaker et al. 2018; Dong et al. 2017; Tolksdorf and Cornel 2017; Watson et al. 2017; Eggimann et al. 2016a, b; Kavvada et al. 2016; Mena-Ulecia and Hernández 2015; Morera et al. 2014; Schuetze et al. 2013). These can include on-site treatment systems (Diaz-Elsayed et al. 2017; Gassie and Engelhardt 2017; Kohler et al. 2017, 2016; Siegrist 2016; Wu and Englehardt 2016). Distributed rainwater capture and natural rainwater treatment systems that infiltrate captured water into local aquifers add to local water supplies and mitigate flooding and pollution caused by uncontrolled runoff (Castonguay et al. 2018; Dong et al. 2017; Kerkez et al. 2016). 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 effects. Water reclamation and reuse facilities provide a drought-resistant water supply while reducing pollution discharges (Sharvelle et al. 2017; Mosher et al. 2016; NAE 2016, 2012; NWRI 2016; Leverenz et al. 2011). 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 United States and Australia. Adding distributed system components can supplement existing

J. Environ. Eng., 2019, 145(10): 04019061

centralized systems and allow them to serve increasingly dense urban areas without the disruption associated with expanding centralized system water distribution and used water collection systems. Source separation can be incorporated into new construction and as existing buildings are renovated (Igos et al. 2017; Penn et al. 2017; Tolksdorf and Cornel 2017; Benami et al. 2016; Landry and Boyer 2016; Udert et al. 2015; Höglund et al. 2002). Separate graywater 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 United States, Europe (e.g., Paris), and Africa.

Peri-urban areas can be served by distributed systems when either a centralized system is not present or it is not cost-effective to extend the centralized system to the developing area (Mena-Ulecia and Hernández 2015). Fecal sludge management approaches can provide effective sanitation, resulting in the protection of public health and the environment (Strande et al. 2014). This approach is particularly applicable in locations such as informal settlements where conventional water supplies may not be available, but it is also certainly applicable when graywater is separately collected and managed as a local water supply. Examples are emerging rapidly, for example, in sub-Saharan Africa (Udert et al. 2015). 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 increase. 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.

Technical challenges remain, however, in identifying optimum system configurations (Renouf et al. 2018; Zischg et al. 2018; Eggimann et al. 2016a, b; Kavvada et al. 2016). Selection of the appropriate configuration requires analysis of trade-offs between transporting materials (water and the constituents they contain), economies of scale for treatment to extract useful products (e.g., water, energy, nutrients, and other materials), and relative locations of resource uses and demands. In general, the transport of water should be minimized to minimize infrastructure cost, energy, and long-term replacement costs, consistent with economies of scale for treatment. New treatment technologies, as discussed earlier, enable reclamation of fit-for-purpose water supplies at relatively local scales, especially if graywater is the raw water source. Use of a raw or used water stream as a source/sink of heat is also best accomplished relatively close to the use site (McNabola and Shields 2013; Meggers and Leibundgut 2011). Organic matter, on the other hand, is best aggregated over a significant portion of an urban area to achieve effective economies of scale for efficient conversion into energy and other useful products such as carbon building blocks (volatile fatty acids and polyhydroxy alkanoates). The most effective scales for nutrient recovery, from either a used water stream or source separated urine, have yet to be established. Fortunately, procedures that consider not only the costs but the logistics for transport and recovery are being developed (Eggimann et al. 2016a, b; Kavvada et al. 2016). Further developments in both transport and treatment technologies can alter the relative costs and economies of scales of available technologies, resulting in changes in the optimal mix over time. This further suggests a need for the development of infrastructure that can be repurposed over time as the location and nature of demands for resources that can be extracted from the urban water cycle change, along with available technologies (Daigger 2017). Experience in repurposing existing infrastructure can lead to insights on how to configure new infrastructure to best facilitate future repurposing.

New and Emerging Issues

New issues related to urban water emerge with some frequency and can dramatically affect both the perception and the reality of overall system performance. Issues often emerge based on scientific findings but before sufficient knowledge is developed to characterize their importance and before effective approaches for addressing them are developed. Microconstituents (e.g., pharmaceuticals, hormones, and other substances present at low concentrations but with potentially important impacts on humans and the environment) represent one such issue that has yet to be resolved despite concerns that have existed for more than two decades. Advanced drinking water treatment technologies, such as advanced oxidation, biological activated carbon, and membrane treatment, are being increasingly implemented, especially in developed countries (Bourgin et al. 2018; Zhang et al. 2018; Mathon et al. 2017; Knopp et al. 2016). Drinking water regulations (e.g., US Safe Drinking Water Act) encourage consideration of emerging constituents, and professional practice concerning their regulation for potable reuse applications is also developing and being adopted. Approaches to addressing the mitigation of their impacts resulting from discharge to the environment in treated effluents are less clear. Microbiological constituents of concern include new pathogens, including viruses, and antibiotic-resistant genes. Their significance for human health continues to unfold. New issues such as microplastics also arise, and historical ones, such as lead in drinking water, can reemerge in some instances.

Issues such as these will, in some but not all cases, necessitate changes to water management practices and approaches. They create uncertainty when they arise, which can slow progress in important areas and also erode public trust in those responsible for water management, depending on how those parties respond. Overreaction can lead to unnecessary expense and waste of resources, while underreaction compromises human and environmental health and can lead to decreased public trust and support. Improved risk management approaches can help in this regard, but they should be coupled with improved understanding of risk perception and communication with the public.

Adapting Institutions and Practices

Current institutional arrangements and professional practices may represent the greatest impediment to fully implementing integrated One Water/resource recovery urban water management systems and receiving their associated benefits. Thus, making the necessary changes in this area may also represent the greatest opportunity for positive change. Transitions are needed to enhance engagement with the public, integrate utility sectors, and broaden practitioners' skill sets beyond technical skills.

An important step is greater engagement with the public (Poortvliet et al. 2018; USEPA 2018; Verstraete et al. 2016; Harris-Lovett et al. 2015). There are several dimensions to the needed engagement, but a key outcome is establishing much greater credibility and legitimacy with the public. As outlined in the discussion of the human right to water and sanitation, service provision must not only be of high technical quality, but it must also engage the public in an open and transparent fashion and provide service that is affordable to all. This must also be accomplished during a time of growing resource scarcity and increasing impact of human populations on the natural environment. Integrated One Water/resource recovery systems offer the potential to provide service that is increasingly tailored to the needs of individual groups of customers, but service providers must understand and quantify these needs in order to meet them. While some service providers are progressing in this area, significant improvement is generally needed, along with research to both advance the underlying science and translate it into practice.

A transition from individual utilities managing components of the urban water cycle to integrated urban water cycle utilities that are truly integrated into the urban areas they serve is also needed. Utilities of this type exist "on paper" in a growing number of locations, and those that exist are increasingly functioning in an integrated fashion. Progress is slow, however, and research is needed that can be rapidly translated to practice to help utilities transition to the integrated urban water cycle organizations that are needed now and will be needed in the future.

A transition in professional practice is also needed (Barron et al. 2017; Luís et al. 2016; Leusbrock et al. 2015; Brown et al. 2013; Wang et al. 2011; Guest et al. 2010; Brown et al. 2009; Guest et al. 2009). Effective water professionals will increasingly require a broader skill set that goes beyond traditional technical capabilities into management and leadership. Engineering bodies of knowledge increasingly describe the range of knowledge and skills required (AAEES and NSPE), but this does not diminish the challenge of acquiring them. Learning and professional development is a lifelong activity and must be supported by organizations, public or private, that employ water professionals (Daigger et al.2017). Professional practice must also evolve to develop and implement solutions that are more adaptable and can be modified more easily as both circumstances and the opportunities afforded by new technologies and approaches become available (Byrne et al. 2017; Garrido-Baserba et al. 2016). We must transition from the design and implementation of systems that are optimal to those that are more adaptable (Daigger 2017, 2011). Design for easy retrofit must become the norm rather than the exception.

Accelerating this myriad of transitions is a daunting task (O'Callaghan et al. 2018; Alegre et al. 2015). Fortunately, research is focused on the processes by which such transitions occur, resulting in an improved understanding of methods to accelerate needed transitions (Rauch et al. 2017; Singh et al. 2017; Watson et al. 2017; West et al. 2017; Brown et al. 2013, 2009). Though just in its infancy when applied to water management, the initial results are encouraging and are needed to allow the water profession to implement needed changes in a timely fashion.

Concluding Comments

This is an exciting time in urban water management as the traditional approach, developed and refined over more than a century, is being replaced by new approaches that are more resource efficient and provide the opportunity for increased service to human populations and the environment. While important components of this new approach—based on integrated hybrid distributed and centralized systems founded on One Water/resource recovery concepts—are developing, many are yet to come. This is a time of reinvention by water researchers and professionals developing next-generation urban water management systems.

References

Alegre, H., S. T. Coelho, J. F. Feliciano, and R. Matos. 2015. "Boosting innovation in the Water Sector: The role and lessons learned from collaborative projects." *Water Sci. Technol.* 72 (9): 1516–1523. https://doi.org/10.2166/wst.2015.362.

Bair, R. A., O. O. Ozcan, J. L. Calabria, G. H. Dick, and D. H. Yeh. 2015. "Feasibility of anaerobic membrane bioreactors (AnMBR) for onsite sanitation and resource recovery (nutrients, energy and water) in urban slums." *Water Sci. Technol.* 72 (9): 1543–1551. https://doi.org/10.2166/wst.2015.349.

Barber, W. P. F. 2016. "Thermal hydrolysis for sewage treatment: A critical review." *Water Res.* 104 (Nov): 53–71. https://doi.org/10.1016/j.watres.2016.07.069.

Barron, N. J., et al. 2017. "Towards water sensitive cities in Asia: An interdisciplinary journey." *Water Sci. Technol.* 76 (5): 1150–1157. https://doi.org/10.2166/wst.2017.287.

Benami, M., O. Gillor, and A. Gross. 2016. "Potential microbial hazards from graywater reuse and associated matrices: A review." *Water Res.* 106 (Dec): 183–195. https://doi.org/10.1016/j.watres.2016.09.058.

Bonastre, A., R. Ors, J. Capella, and M. Peris. 2005. "In-line chemical analysis of wastewater: Present and future trends." *Trends Anal. Chem.* 24 (2): 128–137. https://doi.org/10.1016/j.trac.2004.09.008.

Bourgin, M., B. Beck, M. Boehler, E. Borowska, J. Fleiner, E. Salhi, R. Teichler, U. von Gunten, H. Siegrist, and C. S. McArdel. 2018. "Evaluation of a full-scale wastewater treatment plant upgraded with ozonation and biological post-treatment: Abatement of micropollutants, formation of transformation products and oxidation by-products." *Water Res.* 129 (Feb): 486–498. https://doi.org/10.1016/j.watres.2017.10.036.

Bradshaw, J. L., and R. G. Luthy. 2017. "Modeling and optimization of recycled water systems to augment urban groundwater recharge through underutilized stormwater spreading basins." *Environ. Sci. Technol.* 51 (20): 11809–11819. https://doi.org/10.1021/acs.est.7b02671.

Brewster, T. T., C. M. Mehta, J. Radjenovic, and D. J. Bastone. 2016. "A mechanistic model for electrochemical nutrient recovery systems." *Water Res.* 94 (May): 176–186. https://doi.org/10.1016/j.watres.2016.02.032.

Brown, R., N. Keath, and T. Wong. 2009. "Urban water management in cities: Historical, current and future regimes." *Water Sci. Technol.* 59 (5): 847–855. https://doi.org/10.2166/wst.2009.029.

Brown, R. R., M. A. Farrelly, and D. A. Loorbach. 2013. "Actors working the institutions in sustainability transitions: The case of Melbourne's stormwater management." *Glob. Environ. Change* 23 (4): 701–718. https://doi.org/10.1016/j.gloenvcha.2013.02.013.

Brüchner, I., K. Kirchner, and Y. Müller 2018. "Status quo report on wastewater treatment plant, receiving water's biocenosis and quality as basis for evaluation of large-scale ozonation process." *Water Sci. Technol.* 77 (2): 337–345.

Byrne, D. M., H. A. C. Lohman, S. M. Cook, G. M. Peters, and J. S. Guest. 2017. "Life cycle assessment (LCA) of urban water infrastructure: emerging approaches to balance objectives and inform comprehensive decision-making." *Environ. Sci. Water Res. Technol.* 3 (6): 1002–1014.

Castonguay, A. C., M. S. Iftekhar, C. Urich, P. M. Bach, and A. Deletic. 2018. "Integrated modelling of stormwater treatment systems uptake." *Water Res.* 142 (Oct): 301–312. https://doi.org/10.1016/j.watres.2018.05.037.

Chen, R., Y. Nie, J. Ji, T. Utashiro, Q. Li, D. Komori, and Y.-Y. Li. 2017. "Submerged anaerobic membrane bioreactor (SAnMBR) performance on sewage treatment: Removal efficiencies, biogas production and membrane fouling." *Water Sci. Technol.* 76 (6): 1308–1317. https://doi.org/10.2166/wst.2017.240.

Daigger, G. 2010. "Integrating water and resource management for improved sustainability." In *Water infrastructure for sustainable communities: China and the world*. Edited by X. Hao, V. Novotny, and V. Nelson, 11–21. London: IWA Publishing.

Daigger, G. T. 2007. "Wastewater management in the 21st century." *J. Environ. Eng.* 133 (7): 671–680. https://doi.org/10.1061/(ASCE)0733-9372(2007)133:7(671).

Daigger, G. T. 2009. "State-of-the-art review: Evolving urban water and residuals management paradigms: Water reclamation and reuse, decentralization, resource recovery." *Water Environ. Res.* 81 (8): 809–823. https://doi.org/10.2175/106143009X425898.

Daigger, G. T. 2011. "A practitioner's perspective on the uses and future developments for wastewater treatment modeling." *Water Sci. Technol.* 63 (3): 516–526. https://doi.org/10.2166/wst.2011.252.

Daigger, G. T. 2012a. "Designing and implementing urban water and resource management systems which recover water, energy, and nutrients." In *Water-energy interactions in water reuse*. Edited by V. Lazarova, K.-H. Choo, and P. Cornel. London: IWA Publishing.

Daigger, G. T. 2012b. "A vision for urban water and wastewater management in 2050." In *Toward a sustainable water future: Visions for 2050*.

Edited by W. M. Grayman, D. P. Loucks, and L. Saito. Reston, VA: ASCE.

Daigger, G. T. 2017. "Flexibility and adaptability: Essential elements of the WRRF of the future." *Water Pract. Technol.* 12 (1): 156–165. https://doi.org/10.2166/wpt.2017.019.

Daigger, G. T., S. Murthy, N. G. Love, and J. Sandino. 2017. "Transforming environmental engineering and science education, research, and practice." *Environ. Eng. Sci.* 34 (1): 42–50. https://doi.org/10.1089/ees.2015.0353.

De Albuquerque, C. 2014. *Realising the human rights to water and sanitation: A handbook by the UN Special Rapporteur Catarina De Albuquerque*. Nairobi, Kenya: UNHabitat.

Diaz-Elsayed, N., X. Xu, M. Balaguer-Barbosa, and Q. Zhang. 2017. "An evaluation of the sustainabilty of onsite wastewater treatment systems for nutrient management." *Water Res.* 121 (Sep): 186–196. https://doi.org/10.1016/j.watres.2017.05.005.

Dong, X., H. Guo, and S. Zeng. 2017. "Enhancing future resilience in urban drainage system: Green versus grey infrastructure." *Water Res.* 124 (Nov): 280–289. https://doi.org/10.1016/j.watres.2017.07.038.

Eggimann, S., B. Truffer, and M. Maurer. 2016a. "Economies of density for on-site waste water treatment." *Water Res.* 101: 476–489.

Eggimann, S., B. Truffer, and M. Maurer. 2016b. "The cost of hybrid waste water systems: A systematic framework for specifying minimum cost-connection rates." *Water Res.* 103 (Oct): 472–484. https://doi.org/10.1016/j.watres.2016.07.062.

Fang, L. L., B. Valverde-Perez, A. Damgaard, B. G. Plosz, and M. Rygaard. 2016. "Life cycle assessment as development and decision support tool for wastewater resource recovery technology." *Water Res.* 88 (Jan): 538–549. https://doi.org/10.1016/j.watres.2015.10.016.

Fewless, K., S. Sharvelle, and L. A. Roesner. 2011. *Source separation and treatment of anthropogenic urine*. WERF Project INFR4SG09b. Alexandria, VA: Water Environment Research Foundation.

Garrido-Baserba, M., R. Reif, M. Molinos-Senante, L. Larrea, A. Castilli, M. Vergaguer, and M. Poch. 2016. "Application of a multi-criteria decision model to select of design choices for WWTPs." *Clean Technol. Environ. Policy* 18 (4): 1097–1109. https://doi.org/10.1007/s10098-016-1099-x.

Gassie, L. W., and J. D. Engelhardt. 2017. "Advanced oxidation and disinfection processes for onsite net-zero greywater reuse: A review." *Water Res.* 125: 384–399. https://doi.org/10.1016/j.watres.2017.08.062.

Grant, S. B., et al. 2012. "Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability." *Science* 337 (6095): 681–686. https://doi.org/10.1126/science.1216852.

Guest, J. S., et al. 2009. "A new planning and design paradigm to achieve sustainable resource recovery from wastewater." *Environ. Sci. Technol.* 43 (16): 6126–6130. https://doi.org/10.1021/es9010515.

Guest, J. S., S. J. Skerlos, G. T. Daigger, J. R. E. Corbett, and N. G. Love. 2010. "The use of qualitative system dynamics to identify sustainability characteristics of decentralized wastewater management alternatives." *Water Sci. Technol.* 61 (6): 1637–1644. https://doi.org/10.2166/wst.2010.880.

Harris-Lovett, S. R., C. Binz, D. L. Sedlak, M. Kiparsky, and B. Truffer. 2015. "Beyond user acceptance: A legitimacy framework for potable water reuse in California." *Environ. Sci. Technol.* 49 (13): 7552–7561. https://doi.org/10.1021/acs.est.5b00504.

Hering, J. G., T. D. Waite, R. G. Luthy, J. E. Drewes, and D. L. Sedlak. 2013. "A changing framework for urban water systems." *Environ. Sci. Technol.* 47 (19): 10721–10726. https://doi.org/10.1021/es4007096.

Hodgson, B., S. Sharvelle, J. Silverstein, and A. McKenna. 2018. "Impact of water conservation and reuse on water systems and receiving water body quality." *Environ. Eng. Sci.* 35 (6): 545–559. https://doi.org/10.1089/ees.2017.0157.

Hoekstra, A. Y., and M. M. Mekonnen 2012. "The water footprint of humanity." *Proc. Natl. Acad. Sci. U.S.A.* 109: 3232–3237.

Hoekstra, A. Y., and T. O. Wiedmann. 2014. "Humanity's unsustainable environmental footprint." *Science* 344 (6188): 1114–1117. https://doi.org/10.1126/science.1248365.

Höglund, C. T., A. Senström, and N. Ashbolt. 2002. "Microbial risk assessment of source-separated urine used in agriculture." *Waste Manage. Res.* 20 (2): 150–161. https://doi.org/10.1177/0734242X0202000207.

Huang, J., H. Yu, X. Guan, G. Wang, and R. Guo. 2016. "Accelerated dryland expansion under climate change." *Nat. Clim. Change* 6: 166–171. https://doi.org/10.1038/nclimate2837.

Igos, E., M. Besson, T. N. Gutiérrez, A. B. Bisinella de Faria, E. Benetto, L. Barna, A. Ahmadi, and M. Spérandio. 2017. "Assessment of environmental impacts and operational costs of the implementation of an innovative source-separated urine treatment." *Water Res.* 126 (Dec): 50–59. https://doi.org/10.1016/j.watres.2017.09.016.

IWA (International Water Association). 2016a. *The IWA principles for water wise cities*. The Hague, Netherlands: IWA.

IWA (International Water Association). 2016b. *Water utility pathways in a circular economy.* The Hague, Netherlands: IWA.

IWA (International Water Association). 2016c. *State of the art compendium report on resource recovery from water.* The Hague, Netherlands: IWA.

IWA (International Water Association). 2016d. *Manual on the human right to safe drinking water and sanitation for practitioners*. London: IWA Publishing.

Judd, S., and C. Judd. 2011. *The MBR book: Principles and applications of membrane bioreactors for water and wastewater treatment*. 2nd Ed. Oxford, UK: Butterworth-Heinemann.

Kavvada, O., A. Harvath, J. R. Stokes-Draut, T. P. Hendrickson, W. A. Eisenstein, and K. L. Nelson. 2016. "Assessing location and scale of urban nonpotable water reuse systems for life-cycle energy consumption and greenhouse gas emissions." *Environ. Sci. Technol.* 50 (24): 13184–13194. https://doi.org/10.1021/acs.est.6b02386.

Kavvada, O., K. L. Nelson, and A. Horvath. 2018. "Spatial optimization for decentralized non-potable water reuse." *Environ. Res. Lett.* 13: 064001. https://doi.org/10.1088/1748-9326/aabef0.

Kerkez, B., et al. 2016. "Smarter stormwater systems." *Environ. Sci. Technol.* 50 (14): 7267–7273. https://doi.org/10.1021/acs.est.5b05870.

Knopp, G., C. Prasse, T. A. Ternes, and P. Cornel. 2016. "Elimination of micropollutants and transformation products from a wastewater treatment plant effluent through pilot scale ozonation followed by various activated carbon and biological filters." *Water Res.* 100 (Sep): 580–592. https://doi.org/10.1016/j.watres.2016.04.069.

Kohler, L. E., J. Silverstein, and B. Rajagopalan. 2017. "Risk-cost estimation of on-site wastewater treatment system failures using extreme value analysis." *Water Environ. Res.* 89 (5): 406–415. https://doi.org/10.2175/106143016X14609975747289.

Kohler, L. E., J. Silverstein, and Bl Rajagopalan. 2016. "Predicting life cycle failures of on-site wastewater treatment systems using generalized additive models." *Environ. Eng. Sci.* 33 (2): 112–124. https://doi.org/10.1089/ees.2015.0275.

Landry, K. A., and T. H. Boyer. 2016. "Life cycle assessment and costing of urine source separation: Focus on nonsteroidal anti-inflammatory drug removal." *Water Res.* 105 (Nov): 487–495. https://doi.org/10.1016/j.watres.2016.09.024.

Larsen, T. A., S. Hoffmann, C. Lüthi, B. Truffer, and M. Mauer. 2016. "Emerging solutions to the water challenges of an urbanizing world." *Science* 352 (6288): 928–933. https://doi.org/10.1126/science.aad8641.

Leusbrock, I., T. A. Nanninga, K. Lieberg, C. M. Agudelo-Vera, K. J. Keesman, G. Zeeman, and H. H. M. Rijnaarts. 2015. "The urban harvest approach as framework and planning tool for improved water and resource cycles." *Water Sci. Technol.* 72 (6): 998–1006. https://doi.org/10.2166/wst.2015.299.

Leverenz, H. L., G. Tchobanoglous, and T. Asano. 2011. "Direct potable reuse: A future imperative." *J. Water Reuse Desalin.* 1 (1): 2–10. https://doi.org/10.2166/wrd.2011.000.

Liang, P., R. Duan, Y. Jiang, X. Zhang, Y. Qiu, and X. Huang. 2018. "One-year operation of 1000-L modularized microbial fuel cell for municipal wastewater treatment." *Water Res.* 141 (Sep): 1–8. https://doi.org/10.1016/j.watres.2018.04.066.

Logan, B. E., and M. Elimelech. 2012. "Membrane-based processes for sustainable power generation using water." *Nature* 488: 313–319. https://doi.org/10.1038/nature11477.

Logan, B. E., and K. Rabaey. 2012. "Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies." *Science* 337 (6095): 686. https://doi.org/10.1126/science.1217412.

Luís, A., F. Lickorish, and S. Pollard. 2016. "Evolution of strategic risks under future scenarios for improved utility master plans." *Water Res.* 88 (Jan): 719–727. https://doi.org/10.1016/j.watres.2015.10.057.

Lürling, M., E. Macjay, K. Reitzel, and B. M. Speaks. 2016. "Editorial: A critical perspective on geo-engineering for eutrophication management in Lakes." *Water Res.* 97 (Jun): 1–10. https://doi.org/10.1016/j.watres.2016.03.035.

Magdaleno, F. 2018. "Flows ecology and people: Is there room for cultural demands in the assessment of environmental flows." *Water Sci. Technol.* 77 (7): 1777–1781. https://doi.org/10.2166/wst.2018.075.

Mathon, B., M. Coquery, C. Miege, Y. Penru, and J-M. Choubert. 2017. "Removal efficiencies and kinetic rate constants of xenobiotics by ozonation in tertiary treatment." *Water Sci. Technol.* 75 (12): 2737–2746. https://doi.org/10.2166/wst.2017.114.

McKenna, A., J. Silverstein, B. Hodgson, and S. Sharvelle. 2018. "Modeled response of wastewater nutrient treatment to indoor water conservation." *Environ. Eng. Sci.* 35 (5): 437–446. https://doi.org/10.1089/ees.2017.0161.

McNabola, A., and K. Shields. 2013. "Efficient drain water heat recovery in horizontal domestic shower drains." *Energy Build.* 59 (Apr): 44–49. https://doi.org/10.1016/j.enbuild.2012.12.026.

Meggers, F., and H. Leibundgut. 2011. "The potential of wastewater heat exergy: Decentralized high-temperature recovery with a heat pump." *Energy Build.* 43 (4): 879–886. https://doi.org/10.1016/j.enbuild.2010.12.008.

Mena-Ulecia, K., and H. H. Hernández. 2015. "Decentralized peri-urban wastewater treatment technologies assessment integrating sustainability indicators." *Water Sci. Technol.* 72 (2): 214–222. https://doi.org/10.2166/wst.2015.209.

Moreira, F. C., J. Soler, M. F. Alpendurada, R. A. R. Boaventura, E. Brillas, and V. J. P. Vilar. 2016. "Tertiary treatment of a municipal wastewater toward pharmaceuticals removal by chemical and electrochemical advanced oxidation processes." *Water Res.* 105 (Nov): 251–263. https://doi.org/10.1016/j.watres.2016.08.036.

Morera, S. J. Comas, M. Poch, and L. Corominas. 2014. "Connection of neighboring WWTPs: Economic and environmental assessment." *J. Cleaner Prod.* 90 (Mar): 34–42. https://doi.org/10.1016/j.jclepro.2014.11.047.

Mosher, J. J., G. M. Vartanian, and G. Tchobanoglous. 2016. *Potable reuse research compilation: Synthesis of findings*. Fountain Valley, CA: National Water Research Institute.

NAE (National Academy of Engineering). 2012. *Water reuse: Potential for expanding the nation's water supply through reuse of municipal wastewater*. Washington, DC: National Academies Press.

NAE (National Academy of Engineering). 2016. *Using graywater and stormwater to enhance local water supplies: An assessment of risks, costs, and benefits*. Washington DC: National Academies Press.

Nättorp, A., K. Remmen, and C. Remy. 2017. "Cost assessment of different routes for phosphorus recovery from wastewater using data from pilot and production plants." *Water Sci. Technol.* 76 (2): 413–424. https://doi.org/10.2166/wst.2017.212.

NWRI (National Water Research Institute). 2016. *Evaluation of the feasibility of developing uniform water recycling criteria for direct potable reuse*. Fountain Valley, CA: National Water Research Institute.

O'Callaghan, P., G. Daigger, L. Adapa, and C. Buisman. 2018. "Development and application of a model to study water technology adoption and dissemination." *Water Environ. Res.* 90 (6): 563–574.

Penn, R., M. Schütze, J. Alex, and E. Friedler. 2017. "Impacts of onsite greywater reuse on wastewater systems." *Water Sci. Technol.* 75 (8): 1862–1872. https://doi.org/10.2166/wst.2017.057.

Poortvliet, P. M., L. Sanders, J. Weijma, and J. R. De Vries. 2018. "Acceptance of new sanitation: The role of end-users' pro-environmental personal norms and risk and benefit perception." *Water Res.* 131 (Mar): 90–99. https://doi.org/10.1016/j.watres.2017.12.032.

Qin, Y., H. Kwon, M. Howlader, and M. J. Deen. 2016. "Microfabricated electrochemical pH and free chlorine sensors for water quality monitoring: Recent advances and research challenges." *RSC Adv.* 5 (85): 69086–69109. https://doi.org/10.1039/C5RA11291E.

Rauch, W., et al. 2017. "Modelling transitions in urban water systems." *Water Res.* 126 (Dec): 501–514. https://doi.org/10.1016/j.watres.2017.09.039.

Renouf, M. A., S. J. Kenway, K. L. Lam, T. Weber, E. Roux, S. Serrao-Neumann, D. L. Choy, and E. A. Morgan. 2018. "Understanding urban water performance at the city-region scale using an urban water metabolism evaluation framework." *Water Res.* (Jun) 137: 395–406. https://doi.org/10.1016/j.watres.2018.01.070.

Rockström, J., et al. 2009. "A safe operating space for humanity." *Nature* 461 (7263): 472–475. https://doi.org/10.1038/461472a.

Roehrdanz, P. R., M. Feraud, D. G. Lee, J. C. Means, S. A. Snyder, and P. A. Holden. 2017. "Spatial models of sewer pipe leakage predict the occurrence of wastewater indicators in shallow urban groundwater." *Environ. Sci. Technol.* 51 (3): 1213–1223. https://doi.org/10.1021/acs.est.6b05015.

Schneider, D. 2011. *Hybrid nature: Sewage treatment and the contradictions of the industrial ecosystem*. Cambridge, MA: MIT Press.

Schopf, K., J. Judex, B. Schmid, and T. Keinberger. 2018. "Modelling the bioenergy potential of municipal wastewater treatment plants." *Water Sci. Technol.* 77 (11): 2613–2623. https://doi.org/10.2166/wst.2018.222.

Schuetze, T., J.-W. Lee, and T.-G. Lee. 2013. "Sustainable urban (re-)development with building integrated energy, water and waste systems." *Sustainability* 5 (3): 1114–1127. https://doi.org/10.3390/su5031114.

Sedlak, D. 2014. *Water 4.0: The past, present, and future of the world's most vital resource*. Princeton, NJ: Yale University Press.

Sharvelle, S., N. Ashbolt, E. Clerico, R. Hultquist, H. Levrenz, and A. Olivieri. 2017. "Risk based framework for the development of public health guidance for decentralized non-potable water systems." *Proc. Water Environ. Fed.* 2017 (8): 3799–3809.

Siegrist, R. L. 2016. *Decentralized water reclamation engineering: A curriculum workbook*. Cham, Switzerland: Springer.

Singh, M. P., A. Chakraborty, and M. Roy. 2017. "Developing an extended theory of planned behavior model to explore circular economy readiness in manufacturing MSMEs, India." *Resour. Conserv. Recycl.* 135 (Aug): 313–322. https://doi.org/10.1016/j.resconrec.2017.07.015.

Sinha, E., A. M. Michalak, and V. Balaji. 2017. "Eutrophication Will Increase during the 21st century as a result of precipitation changes." *Science* 357 (6349): 405–408. https://doi.org/10.1126/science.aan2409.

Steffen, W., et al. 2015. "Planetary boundaries: Guiding human development on a changing planet." *Science* 347 (6223): 1259855. https://doi.org/10.1126/science.1259855.

Strande, L., M. Ronteltap, and D. Brdjanovic. 2014. *Fecal sludge management*. London: IWA Publishing.

Sun, L., N. He, T. Yu, X. Duan, C. Feng, and Y. Zhang. 2017. "The removal of typical pollutants in secondary effluent by the combined process of powdered activated carbon: Ultrafiltration." *Water Sci. Technol.* 75 (6): 1485–1493. https://doi.org/10.2166/wst.2017.016.

Tolksdorf, J., and P. Cornel. 2017. "Semicentralized greywater and blackwater treatment for fast growing cities: How uncertain influent characteristics might affect the treatment process." *Water Sci. Technol.* 75 (7): 1722–1731. https://doi.org/10.2166/wst.2017.047.

Tran, N. H., M. Reinhard, and K. Y-H. Gin. 2018. "Occurrence and fate of emerging contaminants in municipal wastewater treatment plants from different geographical regions: A review." *Water Res.* 133 (Apr): 182–207. https://doi.org/10.1016/j.watres.2017.12.029.

Trimmer, J. T., R. D. Cusick, and J. S. Guest. 2017. "Amplifying progress toward multiple development goals through resource recovery from sanitation." *Environ. Sci. Technol.* 51 (18): 10765–10776. https://doi.org/10.1021/acs.est.7b02147.

Udert, K. M., C. A. Buckley, M. Wächter, C. A. McArdell, T. Kohn, L. Strande, H. Zöllig, A. Fumasoll, A. Obserson, and B. Etter. 2015. "Technologies for the treatment of source-separated urine in the eThekwini municipality." *Water SA* 41 (2): 212–221. https://doi.org/10.4314/wsa.v41i2.06.

UN (United Nations). 2012. Vol. 1 of *Managing water under uncertainty and risk: The United Nationals World Water Development Report 4*. Paris: UN.

UN (United Nations). 2015. *Transforming our world: The 2030 Agenda for Sustainable Development*. New York: UN.

UN (United Nations). 2017. "Population division." Accessed August 6, 2018. http://www.un.org/esa/population/unpop.htm.

UN (United Nations). 2018. "World urbanization prospects." Accessed August 6, 2018. http://www.un.org/esa/population/unpop.htm).

USEPA. 2018. *Mainstreaming potable water reuse in the United States: Strategies for leveling the playing field*. Cincinnati, OH: Meridian Institute and Paradigm Environmental.

Verstraete, W., P. Clauwaert, and S. E. Vlaeminck. 2016. "Used water and nutrients: Recovery perspectives in a 'Panta Rhei' context." *Biores. Technol.* 215: 199–208. https://doi.org/10.1016/j.biortech.2016.04.094.

Vo, P. T., H. H. Ngo, W. Guy, J. L. Zhour, P. D. Nguyen, A. Listowsi, and X. C. Wang. 2014. "A mini-review on the impacts of climate change on wastewater reclamation and reuse." *Sci. Total Environ.* 494–495: 9–17.

Wang, J. S., S. P. Hamburg, D. E. Pryor, K. Chandran, and G. T. Daigger. 2011. "Emissions credits: Opportunity to promote integrated nitrogen management in the wastewater sector." *Environ. Sci. Technol.* 45 (15): 6239–6246. https://doi.org/10.1021/es200419h.

Wang, X., G. Daigger, D-J. Lee, J. Liu, N-Q. Ren, J. Qu, G. Liu, and D. Butler. 2018. "Evolving wastewater infrastructure paradigm to enhance harmony with nature." *Sci. Adv.* 4 (8): eaaq0210. https://doi.org/10.1126/sciadv.aaq0210.

Wang, X., P. L. McCarty, J. Liu, N-Q. Ren, D-J. Lee, H-Q. Yu, Y. Qian, and J. Qu. 2015. "Probabilistic evaluation of integrating resource recovery into wastewater treatment to improve environmental sustainability." *Proc. Natl. Acad. Sci. U.S.A.* 112 (5): 1630–1635. https://doi.org/10.1073/pnas.1410715112.

Ward, A. J., K. Arola, E. T. Brewster, C. M. Mehta, and D. J. Batstone. 2018. "Nutrient recovery from wastewater through pilot scale electrodialysis." *Water Res.* 135 (May): 57–65. https://doi.org/10.1016/j.watres.2018.02.021.

Watson, R., P. Mukheibir, and C. Mitchell. 2017. "Local recycled water in Sydney: A political and regulatory tug-of-war." *J. Cleaner Prod.* 148 (Apr): 583–594. https://doi.org/10.1016/j.jclepro.2017.01.174.

West, C., S. Kenway, M. Hassal, and Z. Yuan. 2017. "Expert opinion on risks to the long-term viability of residential recycled water schemes: An Australian study." *Water Res.* 120 (Sep): 133–145. https://doi.org/10.1016/j.watres.2017.04.077.

Wielemaker, R. C., J. Weijma, and G. Zeeman. 2018. "Harvest to harvest: Recovering nutrients with new sanitation systems for reuse in urban agriculture." *Resour. Conserv. Recycl.* 128 (Jan): 426–437. https://doi.org/10.1016/j.resconrec.2016.09.015.

Wikipedia. 2018. "World population estimates." Accessed August 6, 2018. https://en.wikipedia.org/wiki/World_population_estimates.

Wu, T., and J. D. Englehardt. 2016. "Mineralizing urban net-zero water treatment: Field experience for energy-positive water management." *Water Res.* 106 (Dec): 352–363. https://doi.org/10.1016/j.watres.2016.10.015.

Xue, X., T. R. Hawkins, M. W. Schoen, J. Garland, and N. J. Ashbolt. 2016. "Comparing the life cycle energy consumption, global warming and eutrophication potentials of several water and waste service options." *Water* 8 (4): 154. https://doi.org/10.3390/w8040154.

Yousefifar, A., S. Baroutian, M. M. Farid, D. J. Gapes, and B. R. Young. 2017. "Fundamental mechanisms and reactions in non-catalytic subcritical hydrothermal processes: A review." *Water Res.* 123 (Oct): 607–622. https://doi.org/10.1016/j.watres.2017.06.069.

Zhang, Y., B. Wang, G. Cagnetta, L. Duan, J. Yang, S. Deng, J. Huang, Y. Wang, and G. Yu. 2018. "Typical pharmaceuticals in major WWTPs in Beijing, China: Occurrence, load pattern and calculation reliability." *Water Res.* 140 (Sep): 291–300. https://doi.org/10.1016/j.watres.2018.04.056.

Zietschmann, F., G. Aschermann, and M. Jekel. 2016. "Comparing and modeling organic micro-pollutant adsorption onto powdered activated carbon in different drinking waters and WWTP effluents." *Water Res.* 102: 190–201.

Zischg, J., P. Zeisl, D. Winkler, W. Rauch, and R. Sitzenfrei. 2018. "On the sensitivity of geospatial low impact development locations to the centralized sewer network." *Water Sci. Technol.* 77 (7): 1851. https://doi.org/10.2166/wst.2018.060.

Zodrow, K. R., et al. 2017. "Technologies, and complex systems analyses: Emerging opportunities to enhance urban water security." *Environ. Sci. Technol.* 51 (18): 10274–10281. https://doi.org/10.1021/acs.est.7b01679.