Smart Cities and Water Infrastructure

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Summary

Water infrastructure is the system of physical (both built and environmental), social (e.g., governance), and technological elements that move water into, throughout, and out of human communities. It includes, but is not limited to, water supply infrastructure (e.g., pipe systems, water treatment facilities), drainage and flood infrastructure (e.g., storm sewers, green infrastructure systems, levees), and wastewater treatment infrastructure (e.g., pipe systems, wastewater treatment plants, reclaimed water facilities). Smart city approaches to water infrastructure emphasize integration of information and communication technologies with urban water infrastructure and services, usually with the goal of increasing efficiency and human well-being.

Smart water meters, smart water grids, and other water-related information and communication technologies have the potential to improve overall infrastructure efficiency, to reduce water use, to match new water supplies with appropriate water uses, to innovate wastewater treatment, and to protect residents from floods and other water-related climate events. However, without stronger attention to issues of equity, social systems, governance, ecology, and place, a smart city approach to water infrastructure may achieve efficiencies but fail to generate broader socioecological values or to contribute toward climate adaptation.

Keywords: water infrastructure, smart cities, smart water grids, smart water systems, water supply, stormwater systems, wastewater systems, climate adaptation, water systems

Subjects: Management and Planning

Smart Cities and Water Infrastructure: An Evolving Framework for Catalyzing Water Information Flows in Urban Areas

This article provides an overview of smart cities (SCs) and water infrastructure, nested within the overall context of water systems and climate change adaptation. Different disciplines take divergent approaches to SCs, so universal agreement on how to define the concept does not yet exist (Ahvenniemi et al., 2017; Mora et al., 2017). However, definitions usually center on integration of information and communication technologies with urban infrastructure and services, often in order to increase efficiency and human well-being (Birbi & Krogstie, 2017). Urban water infrastructure is the system of physical (both built and environmental), social (e.g., governance), and technological elements that move water into, throughout, and out of cities. It includes water supply infrastructure (e.g., pipe systems, water treatment facilities), drainage and flood infrastructure (e.g., storm sewers, green infrastructure systems, levees), and wastewater treatment systems (e.g., pipe systems, wastewater treatment plants, reclaimed water facilities).

The topic of SCs and water infrastructure connects with diverse areas of environmental science, including hydrology, water quality/chemistry, climate science, ecology, urban ecology, environmental design, and human dimensions of environmental science. Much of the infrastructure-related research draws from urban and regional planning and engineering. In addition, numerous other disciplines examine the connections between SCs and urban infrastructure, including computer science and science and technology studies.

The intersection between the two knowledge sets—the SCs literature and water infrastructure—is relatively new and quickly evolving. This article traces the early beginnings of the SCs framework and links this approach to water infrastructure of urban systems. Given the importance of SCs concepts to the discipline and practice of urban and regional planning, the article also examines how SCs and water infrastructure relate to questions of equity, a core concern of planners. The article presents critiques of the SCs framework in general and as it relates to water infrastructure more specifically. After describing these important questions and concerns, the article shows how a SCs lens has been applied to different urban water infrastructure systems, including water supply, wastewater, and drainage/flood infrastructure. Next, the article provides an overview of how other water-management frameworks and types of information flows might interact with, and elaborate upon, a SCs approach to water infrastructure. Last, the article concludes with a description of essential research directions and a summary of the strengths, weaknesses, and future potential of the SCs approach to water infrastructure.

SCs and Water Infrastructure

Humans have been designing and building water infrastructure for millennia, as they have sought to stabilize water flows in order to provide more constant supplies, to ensure clean water, and to prevent flooding. In contrast, the concept of SCs evolved more recently, with early beginnings in the 1960s, academic research starting in the 1990s, and industry adoption of the term in the mid-2000s (Dameri & Cocchi, 2013; Gabrys, 2014; Gibson et al., 1992; Mora et al., 2017; Neirotti et al., 2014). SCs academic publications first focused primarily on mobility (transportation) and energy and expanded rapidly after the European Union began to fund projects in 2010 (European Commission, 2015; Jucevičius et al., 2014; Mora et al., 2017). As the concept has developed, research and practice have focused on the need for governments and industry to consider SCs approaches to other urban systems, including water infrastructure (European Commission, 2021).

Definitions of SCs: From Efficiency to Utopia

SCs do not yet have a consistently agreed-upon definition, given the diversity of disciplinary approaches as well as divergent adoption by the academy and industry (Ahvenniemi et al., 2017; Mora et al., 2017). Most definitions coalesce around the use of information and communication technologies throughout urban services and infrastructure (Birbi & Krogstie, 2017).

For example: SCs can be described as "an evolutionary transformation in urban infrastructure and management systems combining proliferating information and communication technologies systems with the capture and analysis of real-time data . . . to inform and optimize metropolitan planning and management decision-making" (Young & Lieberknecht, 2019, p. 1677). More simply, the European Commission (2021) defined SCs as "cities using technological solutions to improve the management and efficiency of the urban environment." Information and communication technologies (ICT) range from sensors and meters that gather data, to telecommunication networks that transmit these data, to the data management systems that link sensor and meter data to infrastructure systems. Data can then be used by decision makers to match resources with residents' needs to improve infrastructure and services provision (Gabrielli et al., 2014).

The SCs framework evolved from several disciplines, and therefore it spans an ideological continuum that ranges from a focus on efficiency to a blueprint for holistic urban well-being. Most traditionally, city managers, researchers, and industry leaders have sought to design SCs systems that integrate ICT tools to improve quality of life through efficient service delivery, reduced waste, and diminished environmental harms (Benevolo et al., 2016; Bowerman et al., 2000; Chourabi et al., 2012; Kitchin, 2014; Papa et al., 2013; Streitz et al., 2005). For instance, specifically considering water systems and SCs, Nzimakwe (2020) defined a smart city as a city that: "will increase efficiency, productivity and ecological awareness; it will reduce pollution and improve quality of life in a world of increasing urban complexity" (2020, p. 233).

Scholars and practitioners frequently align SCs with concepts of efficiency (Chourabi et al., 2012; Papa et al., 2013). For example, Gabrielli et al. (2014) advanced the ideas of resource efficiency as a key strategy of a SCs framework, with a focus on improved residents' quality of life as well as reduction of natural resource use. The industry white paper literature puts forth a technocratic, ICT-driven vision of SCs, where city services are integrated for maximum efficiency (Dirks & Keeling, 2010). In this model of SCs, the "Internet of things" drives efficiency and innovation, with little attention paid to broader social or ecological goals (Atzori et al., 2010). In this manner, SCs' focus on efficiency becomes a rationalization of urban processes, via reduction of materials as well as labor and financial expenditures through increased efficiency of service delivery (Young & Lieberknecht, 2019).

Efficiency often focuses on reduction of material, capital, or labor, without a larger consideration of environmental or social context. However, in some cases, efficiency may also result in furthering broader environmental outcomes. For instance, changing production processes to reduce natural resource (material) consumption may also reduce waste of the materials. In this way, SCs can at times proactively addressing environmental challenges by minimizing resource consumption, waste generation, and perhaps even waste-related toxicity and pollution. SCs may also create potential for additional environmental benefits. For example, ICT can be used to integrate variable surges of renewable energy generation into the existing grid (Young & Lieberknecht, 2019).

Some scholarly considerations of SCs provide a much broader definition of the concept than a focus on efficiency. For example, Giffinger and Pichler-Milanović (2007) and Giffinger and Gundren (2010) provided an inclusive definition of SCs in well-cited articles, where they describe SCs as characterized by "[a] smart economy, smart people, smart governance, smart mobility, smart environment and smart living" (2010, p. 7). The "smart mobility" category focuses on mobility and ICT and most closely echoes more typical definitions of SCs, whereas the other five elements describe more broadly a sustainable city. For example, the "smart living" category includes indicators for urban characteristics like health conditions, social cohesion, housing quality, and cultural facilities, which are more socially expansive characteristics than those included in typical definitions of SCs. Caragliu et al., 2013) continued this wide-ranging, interdisciplinary consideration of SCs by including an emphasis on participatory governance and investments in human and social capital. Relatedly, Neirotti et al.'s (2014) consideration of a SC aligns with this more "people-oriented approach" (Ahvenniemi et al., 2017, p. 236) that combines ICT along with social and human infrastructure. These definitions move beyond considerations of efficiency to broader social and ecological outcomes.

In some cases, definitions of SCs verge from broad to aspirational. For example, the World Bank (2012) provided an ambitious definition of SCs:

> Smart cities make urbanization more inclusive, bringing together formal and informal sectors, connecting urban cores with peripheries, delivering services for the rich and the poor alike, and integrating the migrants and the poor into the city. Promoting smart cities is about rethinking cities as inclusive, integrated, and livable.
>
> (World Bank, 2012, p. 1)

Some SC proponents also cite the potential of SC systems to help Global South cities and countries "leapfrog" past inadequate infrastructure systems and, instead, invest in SC approaches to infrastructure that better support future needs (Young & Lieberknecht, 2019). However, although inclusion of marginalized residents, more sustainable urbanization, and integrated land use are all worthy goals, empirical research linking SCs to these outcomes does not yet appear to exist (Mora et al., 2017).

In sum, although there is not a universally accepted definition of SCs, most definitions center on the use of ICT to increase efficiency of urban infrastructure and services. Although efficiency does not necessarily result in increased social and environmental outcomes, a focus on efficiency has the potential to generate additional positive values in addition to the reduction of use of material, capital, and labor. Other definitions promise more aspirational outcomes, such as using SC systems to catalyze the ability of poorer cities to scale up infrastructure quickly and cheaply. However, data from implemented SC projects do not yet support these broader assertions. In addition, a focus on efficiency alone can create problematic outcomes in terms of equity and well-being, which are discussed in more detail in the section "SCs, Water Infrastructure, and Equity."

Water Infrastructure Through the Lens of SCs and Climate Adaptation

Water Infrastructure

A brief overview of the different types of water infrastructure will help us consider how these systems might interact with a SCs framework. Larsen et al. (2016) advanced four goals for the future of water: a safe, affordable water supply; sanitation; drainage provision and flood protection; and high water quality. The authors recommended meeting the goals via innovative approaches to stormwater drainage; increasing water productivity by reducing wasted water, reusing water, and re-treating water; distributed or on-site treatment of wastewater; source separation of human waste before it pollutes water; and institutional and organizational reform. To some degree, water infrastructure can support all these goals and approaches, via water treatment and delivery infrastructure; sanitary sewer collection systems, wastewater treatment systems, and reclaimed water/methane/nutrient collector systems associated with wastewater treatment; stormwater and flood protection infrastructure; and water pollution prevention as well as water treatment systems. These are specific water infrastructure systems that may benefit from a SCs approach. However, although a SCs approach to water infrastructure challenges may provide considerable opportunity for improvements to information flows, water quantity and quality, and accessibility, for the most part, SCs technologies and systems related to water infrastructure are still somewhat underdeveloped in the literature (see, for example, Kasznar et al., 2021).

Likewise, the intersection of SCs, water infrastructure, and climate adaptation appears to be an emerging area without extensive scholarship (Huang-Lachmann, 2019). However, as SCs and climate adaptation research evolves, SC-related improvements to water infrastructure likely will represent a major category of climate adaptation, given the growing academic and practitioner interest in SCs systems and the growing need for climate adaptation. In particular, water-related climate events, such as flooding and drought, will require adaptation planning and strategies that could incorporate SCs within water infrastructure systems.

Water Infrastructure, Climate Adaptation, and Resilience

Water infrastructure intersects with climate adaptation and the related concept of resilience in several critical ways. A brief overview of climate adaptation and resilience will link these concepts more clearly to water infrastructure, as well as help navigate some of the ongoing confusion about these terms (Meerow & Newell, 2019; Weichselgartner & Kelman, 2015).

Climate adaptation focuses on “preparation and adjustment to inevitable impact” of the climate crisis (Berke & Stevens, 2016, p. 283). At times, researchers and practitioners also refer to *climate change planning* or *climate action planning*, although the term *climate action planning* is sometimes limited to climate mitigation (for example, Institute for Local Government, 2020), which refers to reducing, preventing, and stabilizing emissions of greenhouse gases (National Aeronautics and Space Administration [NASA], 2020). Climate adaptation relates to water infrastructure in key ways, including infrastructure that assists in preparation for, response to, and recovery from slow declines in water availability, repercussions from extreme drought, and impacts from flooding. In particular, given the rapidly changing conditions resulting from the climate crisis, climate adaptation fits within broader planning frameworks that center on uncertainty and flexible decision-making (Berke & Lyles, 2013; Berke et al., 2014; Quay, 2010).

Practitioners and researchers sometimes conflate climate adaptation with the concept of resilience (Meerow & Newell, 2019). While the two concepts intersect, resilience and climate adaptation are not synonymous. *Resilience* refers to the ability "to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity" (Meerow & Newell, 2019, p. 39). Defined in this way, resilience comprises an aspect of climate adaptation through which systems respond to climate-related disturbances, such as flooding or drought.

While many academic traditions refer to the concept of resilience, significant disciplinary variation in meaning exists. Engineering considers resilience to be the capacity to recover from, and adapt after, a potentially damaging event (Jin et al., 2021). In a similar way, ecologists describe a resilient ecosystem as one that can return to a stable state after a disturbance (Holling, 1973). However, complications can arise when the term *resilience* is used to describe human systems, especially when the pre-existing state of the system—for example, unsafe housing conditions—is not one to which residents aspire to return. In response, social scientists often qualify that resilience means not just bouncing back, but bouncing forward to better systems of infrastructure, service, and opportunity (Manyena et al., 2011; Smith, 2011). In terms of water infrastructure, that means that as we rebuild communities after climate-related events, we do so in a way that addresses the existing inequalities that many residents face in terms of access to clean water, flood protection, and affordable water supply.

Even with the qualification that resilient human systems should not just bounce back but bounce back better, resilience can still be a problematic concept. For instance, why are some people (often belonging to marginalized populations) expected to be resilient, while other people have access to resources that buffer disaster and damage in the first place? Because of this, critical geographers and others have contested the concept of resilience, citing concerns about racism, poor attention to equity, and lack of resonance of the term with community members, among other critiques (Friend & Moench, 2013; Joseph, 2013; Kaika, 2017; Ranganathan & Bratman, 2019). However, given the engineering discipline's frequent use of the term *resilience* and the relevance of engineering to water infrastructure (for example, see Jin et al., 2021; Li & Yang, 2011), this article refers to resilience when discussing engineering-related aspects of water infrastructure, SCs, and climate adaptation.

Water Infrastructure and SCs

Although early SCs research and practice often focused on transportation/mobility and energy, water systems are increasingly considered to be a critical component of a SCs approach to future urbanization. For example, Nzimakwe (2020) cited the Water World Council's conceptualization of SCs as comprising six elements: smart water, energy, mobility, buildings, public services, and integration (World Water Council, 2017). However, few articles provide empirical documentation of an implemented SCs approach to water infrastructure. Rather, most published research explores different ways to view SCs tools and frameworks as aligned with water infrastructure and water systems goals, such as those advocated by Larsen et al. and others.

For example, Koop and van Leeuwen (2017) considered how SCs may be used to address water-related challenges related to urbanization, climate change, and infrastructure decline; they in turn list a group of challenges, including flooding, water scarcity, water pollution, and public health effects. Koop and van Leeuwen presented SCs as a solution to these challenges but contended that Europe's early approach to SCs, focused on ICT, transportation, and energy, needs to expand to include integration among other systems, including water, wastewater, waste, climate adaptation, and nature. The authors developed a "city blueprint" framework to analyze five water typologies of cities: "cities lacking basic water services, wasteful cities, water-efficient cities, resource-efficient and adaptive cities, and water-wise cities" (Koop & van Leeuwen, 2017, p. 385). They also expand the definition of SCs to include a focus on a coherent long-term social, economic, and ecological agenda designed to maximize co-benefits and minimize cost. Their conceptualization of SCs overlaps with a circular economy approach, in which systems are designed for synergistic material conservation, waste reduction, and expansion of environmental and human well-being, while improving social innovation and governance (European Commission, 2015; MacArthur Foundation, 2013). The authors concluded with a call for the water sector to help lead movement toward water-wise cities by "refocusing radically"—in part through a holistic SCs approach (Koop & van Leeuwen, 2017, p. 418).

Kasznar et al. (2021) developed a literature review framework for SCs infrastructure and included "hydrology" as one of ten SCs infrastructure themes. However, despite the on-the-ground prevalence of water-related infrastructure in cities, the review did not include any articles focused on SCs and water infrastructure, although some reviewed articles focus more broadly on urban water management. In a similar way, Gupta et al., 2020 outlined a SCs approach to increasing water security through more efficient water resource management, but they did not detail any examples of how the SCs framework was implemented (Gupta et al., 2020). These articles point to the growing popularity of a SCs approach to water infrastructure that is not yet matched by empirical evidence that evaluates implementation.

SCs, Water Infrastructure, and Equity

Water infrastructure encompasses key questions of equity. Equity can be described as the state of fair outcomes, achieved through a process that acknowledges and addresses disproportionate harm experienced by particular communities (American Planning Association [APA], 2021; Mobilize Green, 2021). For example, in the case of water and water infrastructure, who has access to safe, clean, and affordable water? Who has adequate sanitation and flood protection? Who is involved in these infrastructure decisions, and what decision-making processes are used?

Despite the importance of equity to all infrastructure decisions, the SCs literature does not yet include a strong focus on fairness and justice. For example, the definitions of SCs discussed at the beginning of this article almost universally did not mention equity. Koning et al. provided a typical example when they said, “The most important objective of smart cities is to meet . . . citizens’ requirements economically and efficiently” (Konig et al., 2015, p. 1), without including equity as a requirement or a characteristic. This outlook matches the general uncritical approach of many articulated SCs goals (Young & Lieberknecht, 2019).

However, a SCs approach to water infrastructure intersects with concepts of equity in numerous ways, even if they are unacknowledged in most literature published to date. Given this relative absence of equity in the SCs water infrastructure literature, it may be helpful to examine SCs water infrastructure through an environmental justice framework as a way to make more concrete the benefits and harms that accompany all decisions about, and investments in, infrastructure. In this way, the environmental justice framework of distributive, procedural, and recognitional justice (Martin et al., 2013; Schlosberg, 2004; Sikor, 2013; Walker, 2012) can be used to help delineate the equity impacts of SCs water infrastructure.

Using this framework, equitable SCs water infrastructure takes into account the past, current, and future distribution of environmental benefits (e.g., access to secure water supplies) and harms (e.g., water pollution). From a procedural justice point of view, equitable SCs water infrastructure would require a decision-making process that is inclusive and democratic. And equitable SCs water infrastructure from a recognitional perspective could be defined as water infrastructure that is designed and implemented in a way that is respectful of identities and culture—for example, a community’s continued use of historic water infrastructure (Lieberknecht, 2019).

Here is a hypothetical example of how a SCs approach to water infrastructure could increase equity, using the environmental justice framework. The SC’s focus on efficiency, and in particular, efficiency of water-use data collection and transfer via smart meters, is structured in part to reduce leakage and waste. A smart water grid could be used to help residents detect leaks and therefore reduce their water use and their water bill, which would be a benefit from a distributive justice perspective for their household economy as well as for the broader ecosystem. As long as utilities installed smart water grids equally across a municipal service area, all residents could benefit, including those who have experienced previous disproportionate harms from unequal infrastructure systems. In this way, a SCs water infrastructure can be implemented to increase benefit for all households. Creation of a fund that offered no-interest loans or grants for household water repairs could provide a pathway for lower-income households to make needed repairs to address any leaks detected by the smart grid system, which would allow these households to fully capture the value of increased information flows provided by a smart water grid. In a similar way, if sensors detected water pollution, and utilities used the data to make needed changes (e.g., replace all lead pipes within a system), a smart water grid could lead to more equitable outcomes for all residents.

Conversely, better information flows around water use may also result in actions that produce disproportionate harms. A hypothetical example of harms stemming from distributive injustice could be a water system in a city with households that cannot afford to pay for water service. For example, in Philadelphia (Pennsylvania), 40% of residents are behind in paying their water bills due to income constraints (Nadolny, 2019). In the hypothetical example, although residents may not be able to pay their bills, they still have access to water service, perhaps in part due to billing inefficiencies by the utility related to inadequate metering systems. If the utility implemented a smart water grid (perhaps in hopes of decreasing leaks, but also with the aim of increasing revenues by improving billing services), and with these improvements some residents began to be charged for water they historically did not pay for due to failing billing and metering systems, the water utility may view the outcome as a case of increased efficiency. However, at the same time, implementation of a smart water grid might limit residents' access to water services, if they cannot afford to pay. A utility may view this as a "smart" consequence and cut off water service to nonpaying customers; in contrast, an environmental justice framework (and the United Nations) would view this as a violation of the human right to water (United Nations General Assembly, 2010).

Consideration of the hypothetical examples helps elucidate the importance of centering equity as SCs water infrastructure continues to evolve. In particular, designing purposeful and equity-centered governance of SCs water infrastructure will buttress outcomes that support environmental justice, as well as broader climate adaptation goals. However, governance of SCs water infrastructure is not yet well explored in the literature. Some considerations of SCs (as applied more broadly than to only water infrastructure) imply that SCs will result in more democratic or even participatory governance (Caragliu et al., 2013). If this were the case, it is possible that SCs could strengthen equitable governance of water infrastructure systems via the "Internet of people"; however, no research yet describes this outcome (Young & Lieberknecht, 2019).

SCs, Water Infrastructure, Resilience, and Efficiency

The concept of water infrastructure resilience, in which water systems are characterized by sufficient redundancy to respond to, and recover from, disturbance, can counteract the SC's goal of efficiency. Evidence from other engineering systems, such as transportation and energy, lends empirical confirmation of conflict between the efficiency and resilience. For example, Ganin et al. considered trade-offs between transportation system efficiency and resilience, defining resilience as "system recovery from additional disruptions" (2017, p. 1). They analyzed road networks in 40 U.S. urban areas and found that many urban road networks that operate inefficiently from day to day also demonstrate the ability to resist disruption, while some efficient road networks exhibit fragility in response to system stressors (such as a disaster). Ganin et al. concluded that roadway projects should incorporate both efficiency and resilience.

Jin et al. (2021) used the example of Winter Storm Uri (in February 2021) that stressed the statewide energy grid in Texas, resulting in severe consequences for humans, infrastructure, and the economy, to demonstrate how a series of decisions by the state that prioritized efficiency led to system fragility. A factor contributing to the damage resulting from lack of energy-system resilience stems from typical risk-based metrics used by engineers, which usually do not take into account low-probability but high-impact events (such as Winter Storm Uri), instead prioritizing system efficiency. Additionally, the risk metrics are often based on historical events, but climate change is occurring so rapidly that historical probability of events does not represent accurate future risk or impact. Jin et al. (2021) argued instead that energy systems must incorporate resilience, which they define as "the capacity to quickly recover from and adapt to disruption" (p. 997). They contended that incorporating a resilience framework as a complement to efficiency will improve system performance under rapidly changing conditions, such as those occurring in the climate crisis. In a similar way, other engineering system frameworks, such as ecological network theory, consider resilience and efficiency to interact synergistically, contributing in tandem to water system sustainability (Li & Yang, 2011).

One strategy for increasing system preparedness for climate events is to add redundancy (Howell et al., 2017). However, addition of redundant elements to a system can increase expense, which counteracts short-term efficiency. In response, the field of "resilience analytics" analyzes system-level impacts on infrastructure to develop recommendations to increase system stability under climate and other stressors (Barker et al., 2017). These interventions increase both climate adaptation and long-term cost savings, potentially increasing efficiency over the long run.

Critiques of SCs Approaches to Water Infrastructure

Concerns about SCs systems pervade the general SCs literature, but less has been written specifically about water infrastructure, perhaps because of the dearth of evaluation of fully implemented smart water systems (SWS; Czaja, 2016; Humphries, 2013). Common critiques of SCs approaches to urban services and infrastructure include social, technological, environmental, and economic challenges. Many of these concerns also may apply to water infrastructure.

For example, any ICT system poses risks associated with data safety, privacy, surveillance, and overdependence on technological solutions (Batty et al., 2012). Several authors have focused on data and security challenges that accompany all ICT systems (Ntuli & Abu-Mahfouz, 2016; Sarkar et al., 2017); these risks will also probably impact water-related ICT. Civil rights and community safety could potentially also be impacted by SCs in general and SWS in particular. For instance, what are the implications of tracking communications, or in this specific case, water use at a granular household and commercial scale (United Nations Human Rights Council, 2015), especially when ICT will often be operated by, and perhaps even owned by, private companies (Humphries, 2013)? Concern about technological limitations also extends to the possibility of bugs or glitches in any ICT system, including water systems, which could disrupt service or result in inaccurate billing.

Conversely, some scholars argue that the primary limitations of SWS are not technological, but economic. For example, Gabrielli et al. (2014) attributed the lag in implementation of smart water metering to economic costs, rather than technological challenges. Given the high cost of SC systems, Topi et al. (2016) recommended a more cautious approach to SC adoption for water infrastructure and instead advanced the suggestion that for some situations, low-tech ("dumb") strategies should preempt SCs applications. For example, utilities should prioritize replacing old appliances with water-conserving versions before installation of a sensor network.

It is also possible that a SCs approach to water infrastructure could result in negative social and environmental outcomes, just as adoption of ICT-enabled ride sharing has created traffic congestion, has reduced mass transit use, and has raised labor concerns (Li et al., 2016; Young & Lieberknecht, 2019). As discussed in the section "SCs, Water Infrastructure, and Equity," questions of equity and access stem from the use of a SCs approach for water infrastructure, although not much has yet been published about these concerns. Environmentally, one of the biggest foreseen challenges of SCs surrounds the escalating energy use associated with expanded ICT systems (Kramers et al., 2014). Given that energy production is one of largest users of water, the increased energy use will also indirectly impact water infrastructure via expanded demands for supply and treatment.

Climate Adaptation, Water Infrastructure, and SCs

From a climate adaptation perspective, planners, engineers, and allied professions will need to create water infrastructure that is responsive to climate events, including, but not limited to, drought, flooding, wildfire, and heat. Specifically, infrastructure related to water supply, wastewater, drainage, and flooding are already being, and will continue to be, impacted by the climate crisis.

Water Supply Infrastructure

Under climate adaptation conditions, water infrastructure that either reduces demand via conservation of water or increases supply through new sources can be used to extend water supply. Much of the SCs water infrastructure literature focuses on smart water grids, which in part can be used to address water supply challenges through water conservation; some research also focuses on rainwater harvesting, which expands supply.

In the SCs field, practitioners and scholars use a wide range of terminology to describe water-supply-related smart systems and components, which can be confusing for researchers and practitioners alike. In the following discussion, the terms *smart water meters* and *smart metering* are generally considered to be technologies that measure water-use data and then transfer the data to water providers (Gupta et al., 2020). The term *smart water grid* is used to describe an integrated collection of water-related sensors. *Smart water systems* move beyond smart water meters to use sensors and ICT to provide real-time data collection about a broader range of water supply and quality characteristics (Gupta et al., 2020). *Smart water management* is sometimes used as a system-level descriptor.

Smart water metering (SWM) has the potential to reduce water consumption by using devices to measure and communicate more detailed data about water use, including water usage reduction associated with two-way communications between the water utility and customers (Gabrielli et al., 2014; Gupta et al., 2020; Taddune, 2018). For instance, if a commercial sprinkler system incorrectly resets and causes extraneous irrigation during nonbusiness hours, a SWM system could alert the utility, allowing it to shut off water use. Or, if a water distribution network has sensors installed throughout a municipality, leaks can be identified and repaired more quickly.

Leak detection is a critical component of water conservation, as municipal water distribution networks are estimated to lose from 20% to 50% of their water supply due to difficult-to-detect leaks resulting from pipe breaks (Alawadhi & Tartakovsky, 2020). Christodoulou (2015) presented an optimal placement of smart sensors used to detect leaks in response to research that identified the need for real-time monitoring of water-distribution network data, such as water pressure, flow, soil moisture, and acoustic data. A similar smart network could also be used to detect water contamination. A related study estimated that in Austin, Texas, a sensored water distribution network could result in 2.9 billion gallons of water saved, which would save $23 million annually (Dickey, 2018). In these ways, SWM and smart water grids could improve overall infrastructure efficiency, reduce water use, and perhaps substitute for new water sources. In particular, these ICT help address a key challenge of water infrastructure systems, which is that much of the pipe infrastructure is underground and not visible, and therefore is difficult to monitor for failures and leaks—as well more challenging for residents and users to envision, value, and appreciate (Lieberknecht, 2019).

In addition, improving the efficiency of water-delivery networks will also indirectly contribute to climate mitigation, as the embodied energy in wasted water further contributes to unneeded greenhouse gas emissions. However, the expansion of smart water grids will increase the energy demand for operating the sensors and communication networks, thereby adding to greenhouse gas emission until utility energy systems are carbon neutral. No definitive energy budget study of the energy impacts of SCs approaches to water systems appears to have been conducted and reported yet.

SWS have been adopted to various degrees around the world. Singapore is home to a real-time monitoring system comprised of sensors and data platforms (Allen et al., 2012), and Brisbane City (Australia) uses ICT to share water data and warnings with the public (Hayes & Goonetilleke, 2012). Fiji, Nepal, the Philippines, and India all have implemented systems (Kim, 2019; Saravanan et al., 2017). In the United States, academic research documented early adoption of SWS by cities in California, but news media in the 2020s reflected widespread adoption throughout the United States that has not yet been reported on in the scholarly literature. Some of the better documented SWS in the United States include the Western Municipal Water District, which serves cities to the east of Los Angeles, and which uses a SWS to provide warnings as well as to operate plants and networks (Leitão et al., 2016). This system has created a 20% decline in both water use and disruption and a 30% decline in energy use. In a similar system, San Francisco's real-time water meters provide consumption data to the utility, helping with identification of water quality problems and leaks (Barsugli et al., 2009).

Although utilities, researchers, and the private sector have expressed strong interest in SWS, and systems are being adopted globally, some argue that a consistent framework to inform design and application would serve as a catalyst for even faster adoption (Li et al., 2020). Li et al. developed a conceptual framework for SWS that outlines future research directions and establishes metrics to ensure success. They recommended research on protection of SWS from cyberattack as well as integration of climate resilience principles. Li et al. recommended two metrics: smartness and cyber wellness. The authors defined smartness as the time interval between system input and output. Cyber wellness is a measure of how well the system stores data before a cyberattack as well as its ability to withstand cyberattacks as long as possible.

The concerns discussed in the section "Critiques of SCs Approaches to Water Infrastructure" all also apply specifically to water supply infrastructure, such as SWM. Cost, energy sources for sensors, data security, and reliability all present challenges to implementation of SWM (Gupta et al., 2020). However, Li et al. (2020, p. 2) contended that installing smart components into an existing water system is a "more cost-effective and sustainable approach" than resizing that same system, suggesting that smart systems might provide high value for water-distribution networks projected to need expansion due to increased water demand.

Although much of the existing literature focuses on how SWS can be used to extend supplies through water conservation, at least one study applied SCs concepts to water sources themselves. Taji et al. (2021) reviewed literature on ICT and water and then used rainwater harvesting to illustrate how ICT might assisting in scaling up rainwater harvesting to a broader geographic scale, which may help make water supply more climate resilient. SWS can also be used to better match recycled/reclaimed wastewater with appropriate uses, which in turn serves as a "new" water source. The next section, "Wastewater Infrastructure," provides more information on the interactions between SWS and wastewater.

Wastewater Infrastructure

Most infrastructure-specific SCs research focuses on the use of ICT with water-delivery systems, but several researchers have focused on SCs wastewater applications. Konig et al. (2015) argued that growing water demand and declining supplies necessitate decentralized wastewater treatment, in which wastewater is collected and treated in a distributed manner. A SCs approach based on remote monitoring and sensing could be used to implement and manage decentralized wastewater systems. In particular, smart decentralized wastewater treatment could use information flows to increase flexibility to changing future demand and to match homogeneous wastewater streams with local use, while remote monitoring and sensing could increase management efficiency.

Nzimakwe (2020) presented an overview of SCs approaches to wastewater, with a specific focus on South Africa. He argued that a smart wastewater grid can serve to make more efficient use of recycled water by better linking data from water treatment systems across a municipality or region. Vakula and Kolli (2017) advocated for retrofitting existing wastewater systems with sensors in order to increase efficiency and better match recycled/reclaimed water (water that has been used once and then treated to the degree needed for specific future uses) to new uses.

Flood, Stormwater, and Drainage Infrastructure

Flooding, stormwater, and urban drainage are key climate adaptation concerns. SCs research in this area has primarily focused on forecasting flood events by linking historic flood data with real-time precipitation data (Barr et al., 2020; Garcia et al., 2020; Loftis et al., 2018; Park et al. 2017; Taddune, 2018). This scholarship is often categorized (via key words or article titles) as sensor-based research, and it does not always explicitly reference SCs, making it possible that this area of research may be left out of other SC summaries and reviews. This may be because at least some of the research is physically based in watersheds outside urban areas; although the watersheds are connected geographically and hydrologically to cities, researchers may not consider their research to be focused on "smart cities" per se, especially if the sensor networks are installed in rural watersheds.

Other climate events and phenomena, such as sea-level rise, storm surge, and saltwater intrusion, will also necessitate changes to, or reconstruction of, water infrastructure, although little SCs literature yet appears to address these infrastructure-specific impacts of climate change. More broadly, as municipalities reconfigure and rebuild water infrastructure in response to climate risk and damage, the integration of smart systems into distributed, modular infrastructure systems may provide some of the promised benefits of SCs systems with the flexibility required of infrastructure investments in areas of high climate risk. As such, lessons from "shrinking cities'" (i.e., cities losing population due to deindustrialization and other trends) infrastructure may serve as a template for climate-adaptive water infrastructure, which will also likely make use of distributed systems (Faust et al., 2016; Gersonius et al., 2013).

Governance and Financing

Practitioners could greatly benefit from research exploring governance and financing of SCs water infrastructure, as little is currently published. For example, Kasznar et al. (2021) noted that most studies do not focus on ongoing financial issues in management and stewardship of SCs infrastructure but instead focus on the early stages of establishing a network. As implementation further develops, scholars should investigate long-term management and stewardship costs associated with smart water infrastructure, along with decision-making power and structures.

Potential Expansions or Evolutions of SCs Approaches to Water Infrastructure

The relatively nascent nature of SCs water infrastructure provides the opportunity to consider alternatives to, or elaborations upon, a SCs approach to water supply, drainage/flooding, and wastewater infrastructure. Other frameworks, such as integrated water-resource management (IWRM), integrated water-cycle management, and water-sensitive urban design, may make positive contributions to SCs approaches to water infrastructure. Concepts of ecological wisdom and local knowledge may also provide useful additions or iterations to current conceptions of SCs water infrastructure.

IWRM is a process that "promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment" (Global Water Partnership, 2014, p. 2). The United Nations and other institutions recognize IWRM as the gold standard for water planning, which includes planning for water infrastructure (Global Water Partnership, 2014; Pahl-Wostl, 2011; United Nations, 2002). One of the challenges of an IWRM approach is the difficulty of integrating diverse information flows about different spatial scales and resource bases (e.g., water systems, land use). Smart systems like sensor networks may provide a pathway for more easily collecting and transferring the distributed information sources that link a municipality with rural areas surrounding it that provide water supply, influence flooding, and receive treated wastewater.

Another approach to resilient water infrastructure is integrated water-cycle management, or a "zero water" system. This framework seeks to increase water-supply security and environmental protection by more efficiently managing municipal water supply, wastewater, and stormwater (Wong, 2006; Wong & Brown, 2011). It focuses on a "fit for purpose" strategy for addressing water sources and quality—where, for instance, wastewater is treated and used again as a nonpotable municipal water supply, rather than being restored to drinking water quality for a nonpotable use, thus saving energy, materials, and capital. A "water-sensitive city" (Brown et al., 2009) moves beyond integrated water-cycle management by aiming to achieve water sustainability through urban design and technology adoption, with a shift in focus toward participation, intergenerational equity, and climate change adaptation. Utilities could apply SCs systems to help better connect different water sources to uses that best fit the quality and quantity of the flows, via infrastructure systems and integrated future design.

More broadly, SCs approaches to water infrastructure have the potential to better link information flows, such as water supply, flooding, and quality, to human use in real time and over large spatial scales. Two approaches to diversifying the information that guides water infrastructure planning could be assisted by the careful design and implementation of a SC approach to water infrastructure. The first, ecological wisdom, can be described as "wisdom of a place"—a property of good design that leverages ecological and cultural knowledge and requires minimal ecological and social intervention (Young & Lieberknecht, 2019). Researchers have described ecological wisdom as the simultaneous achievement of social and ecological sustainability through evidence-based planning interventions requiring minimal input and maintenance to achieve tangible, long-lasting, and positive outcomes (Patten, 2016; Wang et al., 2016). A synthesis between a SC approach to urban systems and ecological wisdom has the potential to integrate technology and information flows with the ecological and social knowledge of a place (Young & Lieberknecht, 2019). Such an approach could help make ecological wisdom more actionable and SC networks more responsive to human knowledge and values.

Last, as communities design and implement climate adaptation for water infrastructure and other systems, the local knowledge held by residents about climate events, the harms they cause, interactions with infrastructure, and potential strategies can be an important addition to new considerations of infrastructure. However, this valuable local knowledge can be difficult to integrate into climate planning and decision-making (Corburn, 2009; Haverkamp, 2017;

Lieberknecht, 2021). Frontline communities often have few opportunities to inform adaptation planning, even though these populations often experience higher climate risk (Shi et al., 2016; Van Zandt et al., 2012). Smart systems could potentially be used to help address the gap between the useful knowledge about climate events, water interactions, and infrastructure held by residents and the linking of this information to utility and other water infrastructure decision makers. The same challenges for other SCs systems, such as concerns about data privacy, security, and equitable access, would exist as well for the collection and transfer of local knowledge related to water infrastructure. However, if utilities were able to address those concerns, SCs systems potentially could provide creative and effective pathways to include local knowledge in the water infrastructure planning processes.

As SCs approaches to water infrastructure continue to evolve, consideration of IWRM, integrated water-cycle management, water-sensitive urban design, ecological wisdom, and local knowledge all provide pathways to push SCs from a dominant focus on efficiency to a more integrated, diversified, and equitable future. Inclusion of locally informed information flows—ranging from data about exurban watershed land uses to micro-effects of climate events on urban flooding—can strengthen SCs approaches to water infrastructure while simultaneously helping to make frameworks often stuck in theory to become more grounded and implementable.

SCs and Water Infrastructure: Research Gaps, Evolving Futures, and SC Pathways to Equitable and Climate-Resilient Urban Water Systems

In addition to increased exploration of the intersections between SCs, water infrastructure, and the frameworks just discussed, other key areas for future research include better integration of concepts of resilience and climate adaptation into SCs water infrastructure, continued knowledge generation about data safety and resistance to cyberattack, and more streamlined processes for data disaggregation and analysis (Li et al., 2020). Other unexplored areas of scholarship include the relationships among SCs, water infrastructure, and privatization of water infrastructure and water sources, which have not yet received much attention in the published literature. Deeper inquiry into the equity implications of applying SCs approaches to water infrastructure will generate both important scholarship as well as critical information for fair and equitable implementation of SCs systems. In addition, given the growing popularity of green infrastructure approaches to urban drainage and flood protection systems, practitioners would benefit from more exploration of SCs approaches to water-related green infrastructure. There also is a gap in the increasing number of SC water supply systems reported upon in the news media and the relatively few case studies discussed in academic literature. Last, much of the existing research about SCs and water infrastructure stems from engineering and computer science; as a result, there is a research gap concerning how SCs relate to water infrastructure through a more expansive definition of "infrastructure"—for instance, a socioecological approach that might also include social infrastructure and governance.

Smart water meters, smart water grids, and other water-related ICT have the potential to improve overall infrastructure efficiency, reduce water use, match new water supplies with appropriate water uses, innovate wastewater treatment, and inform decision makers and residents about water-related climate risks, such as flood warnings. As SCs approaches to water infrastructure continue to be implemented and evaluated, researchers and practitioners have the opportunity to link the new information flows generated by SCs systems to changes in implementation and shifts in scholarly query. Given the broad interest in SCs systems by industry and governments, we can anticipate rapid expansion of SCs water infrastructure networks throughout municipalities around the globe. As this expansion continues, it is critically important for researchers and practitioners to consider the social, technological, environmental, and economic challenges associated with SCs approaches to water infrastructure.

Without stronger attention to issues of equity, social systems, governance, ecology, and place, SCs systems may continue to deliver efficiencies but fail to generate broader socioecological values and achieve climate adaptation. A climate-adapted SC water infrastructure requires equitable governance, inclusion of marginalized populations most affected by climate events, and integration among different urban systems, both built and environmental. Without evolving to include some of the frameworks and information flows discussed in the section "Potential Expansions or Evolutions of SCs Approaches to Water Infrastructure"—including but not limited to IWRM, water-sensitive cities, ecological wisdom, and local knowledge—SCs approaches to water infrastructure will not reach their full potential to contribute to urban spaces where people have access to sufficient, safe, and accessible water; that are safe from floods and other water-related climate events; and that are designed in ways that maximize ecological value while minimizing harm to other human communities as well as the broader ecosystem. Fortunately, a smart water infrastructure system also potentially promises tremendous opportunity to harness SC tools to link place-based knowledge to design, implementation, and management of water systems—a key aspect of climate-adaptive communities.

Further Reading

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