Journal of Environmental Studies and Sciences (2019) 9:90–95
https://doi.org/10.1007/s13412-018-0524-3

Twenty-first century urban water management: the imperative for holistic and cross-disciplinary approach

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Abstract

A symbiotic relationship exists between simultaneous urban development and population growth. Consequences of this relationship have caused deterioration of natural water resources and a continuous need for expansion of urban water infrastructure. In this article, authors discuss the impact of accelerated urbanization on water resources in the twentieth century and the imperatives for holistic and cross-disciplinary approach in water management to meet the twenty-first century quality of life goals. Impediments to futuristic urban water management are also discussed.

Keywords Impact of urbanization · Holistic water management · Cross-disciplinary approach · Quality of life goals

Introduction

In the USA, land development—converting forests and agricultural lands to urban areas—significantly accelerated in the latter part of the twentieth century. Between 1982 and 2001, approximately 34 million acres—about 4 acres per minute—of open space were lost to urban development (USFS 2006). The root of urban development dates back to the nineteenth century Industrial Revolution. Fossil fuel-based power generation enhanced the potential for electricity use and pressurized water transport to distant areas. Job opportunities and other attractions are driving force of metropolis development, i.e., high-density population centers, which encouraged continuous outward expansion of urban areas and population movement from rural areas to urban and suburban areas. As a result, at present, 80.7% of the US population live in urban areas (U.S. Census 2015). A symbiotic relationship exists between simultaneous urban development and population growth. Consequences of this relationship have caused deterioration of natural water resources and a continuous need for expansion of urban water infrastructure.

Authors discuss the impact of accelerated urbanization on water resources in the twentieth century, and the imperatives and impediments for holistic and cross-disciplinary approach in water management to meet the twenty-first century quality of life goals.

Impact of urbanization on water resources

The combined effects of urban development and high water demand have been documented in literature (e.g., Foster et al. 2015; USGS 2016). In summary, impacts include, but are not limited to (1) declining groundwater table due to combined effects of excessive groundwater withdrawal and reduced natural groundwater recharge—low natural infiltration caused by increased paved areas; (2) saltwater intrusion in coastal aquifers caused by pressure imbalance in the interface of freshwater aquifer and saltwater due to declining groundwater table; (3) widespread pollution of surface waters—rivers/tributaries and lakes—and ecosystem degradation caused by both point and non-point sources of pollution, particularly by urban stormwater runoff—it is estimated that approximately 10 trillion gallons a year of untreated urban stormwater runoff enters US rivers and waterways (NRDC 2012).

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Urban water infrastructure

Modern water infrastructure planning and design are based on twentieth century needs/goals and their paradigms/level of technical knowledge. These infrastructures include potable water infrastructure—water source development, water treatment and delivery, and home plumbing systems; wastewater management infrastructure—wastewater (domestic/industrial) drainage, treatment, and discharge network; and urban stormwater drainage infrastructure—the systems of network that removes stormwater runoff from paved surfaces and building rooftops.

We can summarize the primary characteristics of modern water infrastructure as follows: (1) centralized and large-scale systems that serve large areas and populations, (2) generated high volumes of wastewater, (3) depend on myriad of pipe networks that deliver potable water to consumers and drainage pipe networks that transport wastewater and stormwater runoff away from population centers, and (4) depend on significant amounts of fossil fuel-based energy for water treatment and delivery/discharge.

In recent years, many researchers and practicing engineers have pointed out the following problems associated with conventional urban water infrastructure: (1) significant water loss (i.e., non-revenue water) from pipeline break/leakage (Gungor-Demirci et al. 2018; Garcia et al. 2018); (2) contaminant intrusion into drinking water systems via old and deteriorating water distribution systems (Lee et al. 2012); (3) significant energy loss at the distribution systems level (Lee 2015; Dallman et al. 2016); (4) unintended consequences of water demand on water infrastructure and water quality (Tanverakul and Lee 2016; Lee and Whelton 2018); (5) emerging contaminants pharmaceuticals/hormones and other (USGS 2017); and (6) cyber security in large drinking water systems (AWWA 2008).

Transition to the twenty-first century

Based on our observations of both research community/water industry trends, Table 1 summarizes the major characteristics/design philosophy/goals of urban infrastructure (focusing on water) for the twentieth and twenty-first century. It is clear that water, energy, and food nexus—linking basic anthropocentric needs—is a critical emerging theme in the twenty-first century.

Paradigm shift in the twenty-first century

The twenty-first century infrastructure and quality of life goals (Table 1) and challenges noted above demand a paradigm shift toward innovative approaches to effectively cope with existing and emerging problems. A need exists for developing a novel approach that integrates natural and engineered systems into planning and design of urban water infrastructure system: solutions that recognize the nexus between water, energy, and food production in urban environments.

We, the authors, strongly believe that the holistic approach can be best realized by incorporating small-scale decentralized water and energy production systems into urban environments. Lee et al. (2017) discussed the framework for decentralized water and energy infrastructure. The framework provides a solid foundation for a paradigm shift toward water and energy sustainability in urban environments. The decentralized concept is based on maximizing the

Table 1 Infrastructure and quality of life in urban environments (source: authors)

Infrastructure	Twentieth century goals	Twenty-first century goals
Potable water network	Water treatment plants, available tap water in homes and buildings	Sustainable and safe tap water in homes and buildings
Wastewater discharge and treatment network	Sewer disposal pipes for homes/buildings, wastewater treatment	Zero pollutant discharge to natural waters and ecosystem preservation
Stormwater management network	Municipal separate storm sewer system (MS4)	Low impact development, green technologies, urban esthetics
Water source development	Build dams and reservoirs Excessive groundwater withdrawal	Use alternative water sources: rainwater harvesting, stormwater runoff, wastewater reuse
Housing/buildings	Affordability	Energy/water use efficiency
Energy	Fossil fuel imported from outside city boundaries	Shift toward using renewable energy resources
Food	Food imported from outside city boundaries	Organic food products, urban agriculture
Emerging problems in urban water management	–	Emerging contaminants Anthropogenic drought/flood Adopting to climate change Cyber security

development and use of locally available water resources—captured rainwater, stormwater runoff, wastewater, other—and locally available renewable energy resources—solar, wind, micro-hydro power, geothermal, biomass, other—for local consumption. Furthermore, food security in urban areas is an emerging issue. Integrating decentralized urban food production systems into water and energy nexus is an innovative solution that supports sustainable living initiatives and community development in urban areas. Components of the proposed decentralized system are briefly discussed in the following section.

Rainwater harvesting systems

Rainwater harvesting is defined as rainwater capture and use. It can be considered a holistic green technology because it uses captured rainwater, which normally is wasted to drainage network, and therefore reduces urban stormwater runoff and the need for larger stormwater drainage pipes. Furthermore, rainwater harvesting reduces the need for delivery of energy intensive potable water and consequently contributes to water and energy conservation (Younos 2011).

In a rainwater harvesting system, rainwater is collected from building rooftops and paved land surfaces for various indoor uses—potable and non-potable (e.g., flushing toilets) and outdoor uses—fountains, landscape irrigation, community gardens, swimming pools, and recreation ponds. In general, rooftops constitute 25–40% of impervious areas in urban settings. A 100-m^2 rooftop area can collect 1.0 m^3 of water per 1.0 cm of rainfall. Design procedures for rooftop rainwater harvesting systems are described in Sojka et al. (2016). Technological advances in pre-filtration, first-flush design for rooftop rainwater capture combined with advances in small-scale water treatment technologies (for example, reverse osmosis, carbon filter and UV disinfection devices) allows installing small-scale decentralized water treatment systems as satellite systems in buildings to treat and use captured rainwater for potable purposes.

Recent innovative decentralized uses of captured surface stormwater runoff from city-paved areas include using stormwater runoff for landscape maintenance and city esthetics. For example, a 250,000-gal (950,000-l) cistern has been installed beneath the National Mall in Washington, D.C. for turf irrigation and an ornamental water feature at the Cincinnati Zoo replenished by a stormwater capture system (NAP 2016).

Low impact development

Low impact development (LID) is a decentralized green technology that integrates natural and engineered systems in urban water management. Typical LID practices include rain gardens (bio-retention cells), which are typically composed of a mix of components, such as a buffer strip, vegetation, and pond areas (Hirschman and Battiata 2016); green roofs (Orsini et al. 2016); daylighted urban streams–removing urban streams from underground pipes for esthetics and ecosystem preservation purposes (Buchholz et al. 2016). Small-scale onsite wastewater treatment system is considered a LID practice, which relies on natural process and/or mechanical components to collect, treat, and reclaim wastewater for local disposal and use (USEPA 2015; Makoni et al. 2016). The LID is a cutting-edge area of urban water management research and technology.

Wastewater reuse in buildings

Advanced small-scale decentralized water treatment technologies allow decentralized systems to reuse wastewater and function as standalone infrastructure in locations, such as shopping centers, high-rise buildings, hotels, and dormitories. A recent National Academies Press publication provides details on beneficial uses of greywater and stormwater, as well as, risk assessment and benefit cost analysis (NAP 2016). Decentralized wastewater treatment and recycling is an attractive option in high-density population urban areas where water scarcity is prevalent. For example, drought and water scarcity in California has pushed local governments and utilities to consider wastewater reuse as an alternative water source (NAP 2016), and Las Vegas, NV has established a wastewater reuse system (Downing 2018). Chen et al. (2016) discussed case studies and potential for wastewater recycling and reuse in Beijing's high-rise hotels, where about 30% of generated wastewater is treated and recycled within the building.

Integrated renewable energy and water infrastructure

High-energy consumption in the water sector is attributed to water transport and delivery and mostly originates from fossil fuel-based sources with significant economic, social, and environmental impacts (EIA 2016; CRS 2013; Sanders and Webber 2012). Younos et al. (2016) discussed the carbon footprint of water consumption and mitigation strategies in urban environments.

To effectively address long-term energy requirements of water, a gradual shift toward using renewable energy is critical (USEPA 2016; Lee et al. 2017). Significant potential exists to integrate renewable energy, particularly solar and wind, into water infrastructure. Practical applications and novel research in the domain of renewable energy applications for water infrastructure are rapidly evolving (Lee et al. 2017; Tavakol-Davani et al. 2016; Walsh et al. 2014). A few cases of integrating renewable energy in centralized water and wastewater treatment plants do exist (USEPA 2009). However, there is a need and potential to extend uses of renewable energy technologies as a component of a holistic approach that integrates green decentralized systems within the overall urban water management and sustainability. Lee and Younos (2018) discussed examples of powering water infrastructure with renewable energy sources in the USA and other countries.

Water, energy, and food nexus in urban environments

Food production in urban areas, i.e., "urban agriculture," is defined in simple terms as growing, processing, and distribution of food and non-food products through plant cultivation and animal husbandry in and around cities (Mougeot 2000).

Urban agriculture practices include community gardens, backyard gardens, food production in vacant inner-city lots, schoolyard greenhouses, restaurant-supported gardens, backyard orchards, rooftop gardens, and green houses. Noted benefits of urban agriculture include (1) conservation of water and energy resources; (2) environmental stewardship; (3) lower food cost; (4) job creation and economic development in low-income areas; (5) community revitalization; (6) health protection—fresh produce, improved nutrition, and opportunities for exercise. Locally, available water, such as captured rainwater and renewable energy can be significant resources that could support urban agricultural systems. Parece et al. (2016) described technical aspects of integrating rainwater harvesting and urban agriculture. In their study, geospatial analysis was applied to identify land parcels suitable for community gardens and buildings where rainwater capture and use were possible.

Discussion and future roadmap

Holistic approach for urban water management and the critical role of decentralized water and energy infrastructure were discussed in this paper. It should be noted that decentralized and small-scale water and energy infrastructure can reduce cyber security risks associated with large potable water infrastructure and electricity grid, and could be an effective strategy for coping with consequences of climate change, i.e., extreme weather conditions.

Figure 1 shows five core factors—science and technology, policy and regulation, education, practice, and public perception—that can drive holistic urban water management in the twenty-first century. Below, we discuss the impediments and possible roadmap for successful implementation of holistic water management in urban environments. In our opinion, the following are major reasons impeding holistic urban water management approach in urban environments: (1) traditionally conservative attitudes within water resources engineering/planning community, (2) silo-mode college curricula in water management, (3) regulatory and policy gaps and hurdles, and (4) public perception. These impediments are explained in the following.

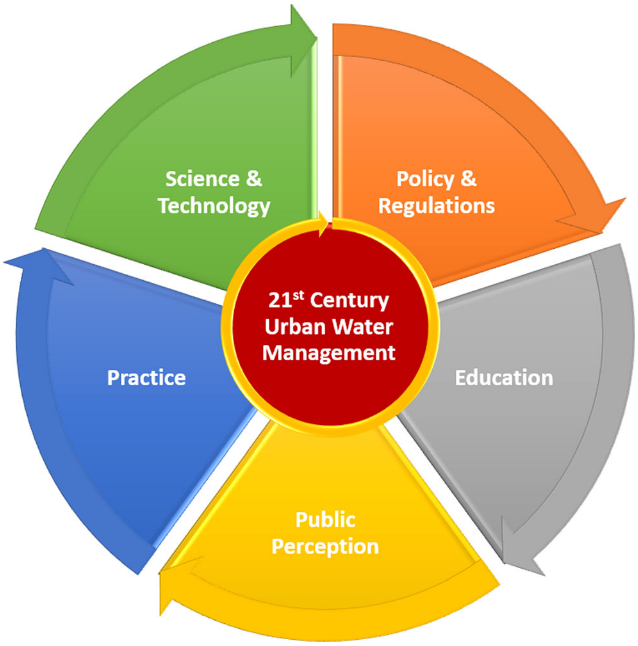

Fig. 1 Ingredients for twenty-first century holistic urban water management (source: authors)

Although there are some exemplary cases of incorporating new thinking in urban water management (e.g., Morton 2013), many engineering/planning experts who work on planning and design of urban water management tend to follow the twentieth century quality of life goals as exhibited in Table 1. A simple illustrative example is the issue of urban stormwater management, where stormwater drainage network is continuously expanded with less consideration for alternative green technology approaches. To some extent, this impediment can be associated with existing silo-mode college curricula, which fails to prepare future engineers and planners to attain the quality of life goals of the twenty-first century. Complex and challenging issues facing urban water management require a cross-disciplinary learning approach—integrating engineering, hydrologic sciences, chemical and biological sciences, plant and food production sciences, geospatial technologies, information technologies/data management sciences, cyber infrastructure, and socioeconomic sciences.

In general, policy-making is a long and tedious process, often affected by political decisions and, in most cities, does not keep up with technological advances. There is a significant need for updating policies and regulations, such as changes in zoning ordinances and building codes, and economic incentives to promote implementation of decentralized water and energy infrastructure. In this vein, it is equally important to have a deeper understanding of water utility operations and management and coordinate among various involved stakeholders (Güngör-Demirci et al. 2018a, b).

Last, but not least, public perception remains a serious impediment in urban water management. For example, in many localities, captured rainwater is perceived as gray water, and citizens (and some regulatory agencies) are reluctant to accept rainwater and wastewater reuse as an alternative to conventional potable water source. Thus, a focus on citizen education and K-12 curricula should be a top priority to change public perception.

As we noted above, the decentralized concept is based on maximizing the use of locally available water and renewable energy resources. Furthermore, integrating decentralized urban food production systems into water and energy nexus can be an innovative solution that supports sustainable living and community development in urban areas. Therefore, it is essential that we encourage local governments to consider the vision for implementing decentralized infrastructure into retrofits and new developments/constructions. We firmly believe that this approach can best address water and energy problems at the local level and enhance food security in urban environments.

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