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# A Changing Framework for Urban Water Systems

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Urban water infrastructure and the institutions responsible for its management have gradually evolved over the past two centuries. Today, they are under increasing stress as water scarcity and a growing recognition of the importance of factors other than the cost of service provision are forcing a reexamination of long-held ideas. Research and development that supports new technological approaches and more effective management strategies are needed to ensure that the emerging framework for urban water systems will meet future societal needs.

## ■ INTRODUCTION

Over the last few decades, society has become increasingly aware of the vulnerability of urban water infrastructure as well as the water supply catchments and surface waters where sewage effluent and urban runoff are discharged. It is apparent that many of the centralized water supply and treatment strategies developed in Europe and North America during the period of industrialization in the nineteenth and twentieth centuries will not be able to meet future challenges. In industrialized countries, these challenges include climate variability, changing population densities, and the need to protect or improve ecosystems affected by infrastructure development. Existing systems in many industrialized countries are also reaching the end of their design lifetimes. Cities are thus facing seemingly insurmountable financial challenges related to replacing water distribution pipes and sewers while simultaneously upgrading treatment plants to address threats and legal requirements posed by nutrients, wastewater-derived organic compounds, and other pollutants.[1] In developing countries, the challenges posed by lack of capital to invest in large centralized water and sanitation infrastructure and rapid urbanization are often complicated by semiarid climates that are poorly suited for water-based sewage conveyance.[2]

Coincident with the growing realization of the inadequacy of our current approach to managing the urban water cycle, rapid developments in biotechnology, materials science, sensors, and computing are giving rise to technologies that have the potential to revolutionize urban water systems. In addition, an improved understanding of the ability of managed natural systems (e.g., constructed wetlands, managed aquifer recharge) to function as components of urban water infrastructure is opening up options that are more attractive to the public and less expensive to operate than conventional treatment plants. The existence of these alternative approaches is creating a new institutional framework, informed by decades of operational experience and strategies pioneered in the energy and transportation sectors, that supports a fundamental shift in the management of urban water systems.

In recent years, industrialized countries, such as Australia, Israel, and Singapore, and arid regions, such as the Southwestern United States, have made major technological and institutional improvements in their urban water systems. These changes have been motivated mainly by the need to increase water availability in the face of severe shortages.[3] In many Central and Northern European countries, where water shortages have been less of a problem, efforts to apply the principles of integrated urban water management, driven by a growing societal interest in promoting sustainability, have fostered changes.[4]

For a new framework for urban water systems to become fully established industrialized countries and to serve as a model for future water management in developing countries, sweeping changes will be needed in the ways that engineers and mangers of urban water systems approach the planning, design, and operation of urban water infrastructure. For this change to take hold, it will be necessary to embrace not only new technologies but also innovative management strategies that can create more resilient, economically sustainable water systems that will better serve society's future needs. Public acceptance, particularly for new technologies and unfamiliar practices (e.g., greywater recycling), will require more effective communication about

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the need for change and the relative risks of different approaches to water provision and waste treatment.

The difficulty in changing the framework for managing urban water systems reflects the long-term nature of investments in water infrastructure as well as the crucial role of water infrastructure in protecting public health and the environment. Risk-averse behavior by decision-makers frequently stymies attempts to innovate because the large financial investments typical of water infrastructure require assurance that they will perform as planned. Efforts to change the existing framework are further hampered by historic factors that have resulted in the division of responsibilities for different aspects of urban water systems among several agencies or institutions, each of which may be subject to conflicting requirements or expectations.[5]

There is an important role for researchers in developing a new framework to overcome these challenges. Research is needed to create new technologies, to decrease the uncertainties associated with system performance, to develop bridging technologies that facilitate the integration of new approaches into existing systems and to promote a systems approach to infrastructure planning. Collaborations between teams of engineers, city planners, and social scientists also will be needed to develop new forms of water governance and management, including ways of improving public engagement.

For the purpose of understanding current and future research and development needs, the elements of the new framework for urban water systems can be subdivided into four themes:

- *Increasing water availability* through improved system efficiency, demand management, desalination, stormwater harvesting, and water reuse;
- *Broadening treatment options* by developing technologies that lead to more resilient systems, link water quality to its intended use and incorporate managed natural systems into urban water infrastructure;
- *Considering wastewater as a resource* through energy and nutrient recovery; and,
- *Establishing an enabling environment* by explicitly addressing institutional and management challenges related to a need to account for nonmonetary benefits, manage tradeoffs among alternatives and more effectively engage stakeholders.

**Increasing Water Availability.** In the past, the problem of inadequate water supply was often solved by major infrastructure projects, either for conveyance of imported water or for water storage.[3] Over the past several decades, conservation has also played an increasingly important role in satisfying demand, through the adoption of water-saving devices in the residential, commercial and industrial sectors. Singapore, for example, employed consumption-based tariffs and a water conservation tax to achieve an 11% reduction in average monthly water consumption between 1995 and 2004.[6] While water use efficiency will continue to serve as an important component of urban water supply in coming decades, there are signs that it will eventually become less attractive, as the least expensive water-conserving appliances and industrial process modifications are implemented.[7]

The reduction of water losses in the distribution system offers another means of making urban water systems more efficient. In the U.S., an average of 14% of treated water is lost to leaks. The situation is even worse in many developing countries, where losses of up to 40% are common.[8] Modern asset management schemes are capable of achieving substantial water savings through more effective leak detection and prioritization of pipe repair and replacement. The coming shift to real-time water metering and pressure sensors will create opportunities to identify and repair water leaks in a more cost-effective manner.[9] Furthermore, real-time data will provide opportunities to minimize overpressurized sections of pipes or pressure surges that are often responsible for substantial water losses.[10] These control measures may also make it possible to increase pressure automatically in response to firefighting activities or main breaks—overcoming perceived impediments that often hampered previous efforts to manage pressure more effectively.

Although many challenges remain with regard to environmental impacts, desalination is now considered a viable option for urban water supply, particularly in situations where either climate change or short-term events (e.g., catastrophic floods) compromise water quantity and quality. The acceptability of seawater desalination has come about principally because of the reduction in power consumption of the reverse osmosis stage due to improved membrane design and implementation of energy recovery technologies.[11] Australia's driest capital city of Perth, for example, will receive almost half of its water supply from two seawater desalination plants of combined capacity of up to 400 ML/day once commissioning is completed in 2013. The increased greenhouse gas emissions associated with operation of the desalination plants will be offset by energy from wind farms and arrays of solar panels.

Seawater desalination plants have also either been constructed or are close to commissioning for other Australian capital cities of Melbourne and Sydney, though the decision to construct these plants has been far more controversial than was the case for Perth principally because of the cyclical fluctuations in water demand and the potential for satisfying water needs with other approaches. In Sydney, a 250 ML/day desalination plant (upgradable to 500 ML/day) is expected to run at full capacity only when total reservoir storage falls below 70% and would be put into standby mode when levels reach 80%.[12] Although this approach may be appropriate from the standpoint of minimizing energy consumption, financing for the project has been challenging because of the need to incorporate costs associated with intermittent operation into water usage charges.

Stormwater harvesting couples flood control and urban runoff management with urban water supply by capturing runoff and recharging it to drinking water aquifers or by reusing stormwater for nonpotable uses. This underappreciated water source is already an important part of the supply for some cities. For example, the Los Angeles County Department of Public Works operates 27 spreading basins that recharged 149 million $m^3$ of surface runoff in the 2011–2012 water year.[13] Although some of the recharged runoff consists of dry weather flows from rivers that receive wastewater effluent, the majority of the recharged water is associated with wet weather flows. Other parts of Los Angeles are pursuing an effort to further enhance the recharge of stormwater as part of a strategy for coping with possible decreases in imported water sources.[14] More research is needed to assess the water quality implications of this practice, and, when necessary, integrate passive treatment processes into recharge systems.

The reuse of municipal wastewater has the potential to play an important role in expanding urban water supplies.[3] In water scarce regions, like Southern California, this expansion is also motivated by lower specific energy needs of recycled water (1.8–2.6 $kWh/m^3$) relative to seawater desalination (3–4 $kWh/m^3$) and imported surface water (2–3.2 $KWh/m^3$).[15] Many of the first generation water reuse systems built in the U.S., Southern Europe, and Australia subjected the effluent from existing centralized wastewater treatment systems to additional treatment to inactivate waterborne pathogens prior to application for landscaping and agricultural irrigation. However, attempts to expand these systems have often been limited by the expense of constructing separate water distribution systems and the need for reliable systems to prevent inadvertent cross connections of those networks with potable water systems.[3,16]

To avoid the need to locate reclamation facilities near users or to build dual distribution networks, some cities have turned to potable water reuse. For example, Singapore's NEWater Project will soon produce around 550 ML/day of reverse osmosis-treated water from the city's wastewater treatment plants. While much of the reclaimed water is used by industrial users who value the low salinity water, the reclaimed water provides around 2% of Singapore's potable water supply and will increase in the future.[3] Following the success of projects operated by the Orange County Water District, Singapore's Public Utility Board and several other utilities, utilities in Texas and New Mexico have begun to plan and build potable reuse projects in which reclaimed water will be piped directly into raw water storage and conveyance systems.[17] However, widespread adoption of potable reuse is uncertain, as factors related to public perception and concerns about the decision-making process have sometimes led to rejection of proposed water reuse projects.[3,18]

**Broadening Treatment Options.** Recently, several large water reuse projects have expanded their user base by creating separate treatment trains tailored to the intended use of the water. For example, the Edward C. Little Water Recycling Facility in Los Angeles produces five different types of water to meet the needs of local customers who use it for applications including cooling towers, industrial boilers, landscape irrigation, and recharge of groundwater. This more flexible approach to water reuse has the potential to improve the economic efficiency of the process by providing a means of adjusting the amount of water passing through each of the plant's treatment trains as demands change over a period of several years. Such tailored water systems stand in contrast to reclamation facilities serving urban landscape irrigation projects that operate significantly below capacity or sit idle during seasons when irrigation water is not needed, as well as projects where reclaimed water is dedicated to a single power plant or industry—an inflexible situation that can create disincentives for conservation.

Decentralized systems have the potential to further increase flexibility and reduce energy consumption and lower the costs of infrastructure replacement. While reliability is still a major concern for decentralized water reclamation systems, advances in sensors and autonomous control systems are increasing confidence in system performance.[19] Emerging technologies that go far beyond traditional monitoring and control protocols may enable deployment of remotely operated satellite wastewater treatment plants at the scale of a single building or a cluster of homes. With this modern version of on-site wastewater treatment, the need to maintain expensive sewer infrastructure can be reduced and nonpotable water reuse can be practiced with fewer risks of cross connections. To date, such approaches have mainly been exploited in demonstration projects or in sensitive remote locations, such as the Monte Rosa Hut in Zermatt, Switzerland.[20] In the near future, such systems may be used in new housing developments where construction can more readily realize the full benefits of lower consumptive water use and the disposal of smaller volumes of sewage can be properly incorporated into building design and construction.

For drinking water supply, decentralized solutions (e.g., point-of entry systems, roof water collection) have usually been considered viable only for small service areas. A major impediment to expansion of such decentralization to urban systems is the need to frequently monitor water quality within the household.[21] Further development of reliable real-time monitoring systems and successful demonstration projects are needed before decentralization will have a major impact on potable water supply.

Actively managed natural systems, such as constructed treatment wetlands, bioinfiltration basins and managed aquifer recharge systems are increasingly viewed as valuable components of urban water infrastructure that provide multiple benefits. A managed natural system consisting of a wetland coupled to a groundwater infiltration system can add resiliency to the water supply portfolio, enhance urban aesthetics, provide wildlife habitat, and improve water quality. An example of one such system can be found in the Santa Ana River in Southern California, where about half of the flow of an effluent-dominated river passes through the Prado Wetlands before flowing downstream to an engineered groundwater recharge facility.[3]

The main impediments to widespread adoption of managed natural systems as part of urban water infrastructure are related to concerns about long-term performance, relatively large land requirements and inability to provide uniform treatment efficacy, especially during winter, when plants and microbes tend to be less active. To make managed natural systems more reliable, cost-effective and sustainable, we envision the development of modular, unit-process systems that incorporate the latest developments in real-time controls to monitor and adjust performance. The use of wireless devices to manage bioinfiltration systems and cisterns for control of combined sewer overflows represents a current application of such technology.[22] Similar applications of wireless devices could be used to increase hydraulic residence times in constructed wetlands, manage bioinfiltration basins to favor denitrification, and avoid pulses of water that tend to mobilize waterborne pathogens.

The implementation of land use policies that strengthen watershed protection can be viewed as a means of broadening treatment options by eliminating the need to invest in conventional water treatment infrastructure. For example, an agreement involving land acquisition, conservation easements, setbacks, buffer zones, and land trusts allowed New York City to forego construction of a filtration facility for its Catskill/Delaware watershed (which had estimated costs of $US 6 billion for design and construction and $US 300 million for annual maintenance and operation).[8]

**Considering Wastewater As a Resource.** In addition to its role as a potential water source, wastewater also contains valuable resources, including thermal energy, organic compounds and nutrients. Heat recovery from either sewage leaving the home, within sewers or at the treatment plant has already been practiced in Switzerland, Germany and other countries.[23] A shift from energy-intensive aerobic treatment to anaerobic treatment at centralized or decentralized plants may result in reduced energy use with the simultaneous recovery of more biogas that can be used to produce electricity.[24] This fundamental shift in treatment technology could create incentives for renewing aging wastewater treatment infrastructure with additional financing leveraged by the promise of reduced operating costs and lower greenhouse gas emissions.

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Even without a complete shift to anaerobic wastewater treatment, existing solids handling processes can be better exploited for energy production. For example, Oakland's East Bay Municipal Utility District has been operating a codigestion program since 2001. As part of the program, the addition of high-strength organic wastes from wineries, poultry farms and restaurants to the plant's digesters has increased the plant's on-site power generation to a point where the facility generates more electricity than it consumes.[25]

Energy management in wastewater treatment plants can be further optimized by improved nitrogen management. Autotrophic anaerobic oxidation of ammonia with nitrite (Anammox) can be used in place of conventional nitrification and heterotrophic denitrification to reduce the energy demand associated with aeration and eliminate the need for a supplemental organic carbon source.[26] Alternatively, ammonium in wastewater can be converted into nitrous oxide that can be used to increase energy production during biogas combustion.[27]

Phosphorus and nitrogen also can be recovered from wastewater.[28,29] The traditional approach to resource recovery involved the application of biosolids to land as fertilizer and soil conditioner. But over the past few decades, the practice has become more controversial due to the presence of contaminants [30] and is even forbidden by law in some European countries. Source-separating (no-mix) toilets can facilitate nutrient recovery without introducing contaminants to agricultural soils while simultaneously reducing the volume of wastewater to be treated. However, on-site urine management is expensive and the technologies are considered risky by wastewater professionals in developed countries.[2] Further research is needed to expand the use of this practice.

**Establishing an Enabling Environment.** A wide range of new approaches to urban water have been demonstrated in small-scale projects and some have even been applied in major municipalities, especially in water-scarce regions. Yet even in the face of pressing need, uptake of new ideas has often been controversial and sometimes even unsuccessful.[31] Research into the factors leading to success imply a need for the creation of an enabling environment that incorporates factors including government support; adequate legal and regulatory frameworks, institutional arrangements, and financing opportunities; the availability of necessary skills and capacities; and socio-cultural acceptance.[32] If decisions about urban water management options are to go beyond the financial consequences for the utility responsible for the project, it will be necessary to account for multiple benefits (e.g., ecosystems, aesthetics). Models and decision support tools must be developed to predict outcomes, address uncertainty and quantify nonmonetary factors associated with changes in urban water systems.[33,34] Tools to assess stakeholder preferences, such as willingness-to-pay (WTP)[35] and multicriteria decision analysis (MCDA)[36] can provide insight into the feasibility of various options and/or the obstacles that might arise in their implementation. Explicit illustrations of linkages and trade-offs can be provided by integrated approaches, such as life cycle analysis (LCA), material flow analysis (MFA) and environmental risk assessment.[37] Such tools are now being used routinely by urban water authorities in Australia to assist urban water utilities in incorporating subjective issues in the decision-making process.[38]

Yet all of these tools and approaches can be easily undermined if public opinion turns against a project. Stakeholder engagement has been promoted as a means to gain legitimization and acceptance of new ideas, though these benefits have not always been fully realized.[39] One possible explanation is that inadequate stakeholder engagement and participation reduces political support for projects and empowers critics. Alternative models for institutional decision-making processes that incorporate early and substantial involvement of stakeholders and allow members of the public to identify alternative technical options have been proposed as one possible solution.[33,40] Additional research is needed to determine the appropriate level of stakeholder engagement in different communities.

**A Lasting Change in Urban Water Management.** Will a new framework that supports resilient and effective urban water systems become the dominant, worldwide paradigm?

The management of urban water infrastructure tends to be conservative; a lasting change can only occur when the shortcomings of the existing system become too big to ignore and the community reaches a consensus that viable alternatives are available. It is likely that we are reaching the time when these conditions will be met. Perhaps the change will happen after a few more high-profile events like the decade-long drought experienced by Australia. Alternatively, it is possible that the financial strain associated with operating centralized urban water infrastructure in a time of increasing energy prices and smaller investments by governments will create incentives for new business and governance models to develop. The future of urban water systems requires us to overcome the challenges described above and to design, operate, and manage water systems in fundamentally different ways. This will require that decision-makers, engineers, researchers, and educators adopt new approaches to problem solving.

Engineers will have to embrace the complexities of managing unfamiliar systems that, unlike conventional systems, are not designed to be fully controlled. Decentralized systems and managed natural systems require flexibility, effective communication, and risk management that may be unfamiliar and even unwelcome in public utilities.

For water managers, environmental regulators, and elected officials, the planning process will need to be adapted to encompass measures of performance beyond the finances of a single utility or political entity. New tools will be needed to quantify nonmonetary benefits and to create incentives for organizations to adopt approaches that lead to better overall outcomes. Participatory processes will need to be established in which citizens can be actively involved in making decisions that affect their lives, even to the point of leading the decision-making process.

Researchers will need to pay more attention to the potential impacts of new technologies on overall system performance. Efforts to create new treatment technologies and assess their performance at pilot- and full-scale conditions will need to be accompanied by the collection of data for the assessment of system-level performance of urban water infrastructure. Widespread reliance on managed natural systems will require the integration of knowledge and tools from the basic sciences, such as microbiology, ecology and geochemistry along with computer science and control theory into practice.

Future water management will necessitate changes in the ways that environmental engineers are educated. There will still be a need for training in traditional aspects of engineering related to the design and operation of treatment systems. In addition, efforts will be needed to provide a better understanding of natural processes, the skills needed to work with complex institutional systems, and the capacity to pursue a meaningful partnership with citizens whose lives will be affected by how well (or badly) our urban water systems are managed.

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**Notes**

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