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Evolving Urban Water and Residuals Management Paradigms: Water Reclamation and Reuse, Decentralization, and Resource Recovery

Glen T. Daigger*

ABSTRACT: Population growth and improving standards of living, coupled with dramatically increased urbanization, are placing increased pressures on available water resources, necessitating new approaches to urban water management. The tradition linear "take, make, waste" approach to managing water increasingly is proving to be unsustainable, as it is leading to water stress (insufficient water supplies), unsustainable resource (energy and chemicals) consumption, the dispersion of nutrients into the aquatic environment (especially phosphorus), and financially unstable utilities. Different approaches are needed to achieve economic, environmental, and social sustainability. Fortunately, a toolkit consisting of stormwater management/rainwater harvesting, water conservation, water reclamation and reuse, energy management, nutrient recovery, and source separation is available to allow more closed-loop urban water and resource management systems to be developed and implemented. Water conservation and water reclamation and reuse (multiple uses) are becoming commonplace in numerous water-short locations. Decentralization, enabled by new, high-performance treatment technologies and distributed stormwater management/rainwater harvesting, is furthering this transition. Likewise, traditional approaches to residuals management are evolving, as higher levels of energy recovery are desired, and nutrient recovery and reuse is to be enhanced. A variety of factors affect selection of the optimum approach for a particular urban area, including local hydrology, available water supplies, water demands, local energy and nutrient-management situations, existing infrastructure, and utility governance structure. A proper approach to economic analysis is critical to determine the most sustainable solutions. Stove piping (i.e., separate management of drinking, storm, and waste water) within the urban water and resource management profession must be eliminated. Adoption of these new approaches to urban water and resource management can lead to more sustainable solutions, defined as financially stable, using locally sustainable water supplies, energy-neutral, providing responsible nutrient management, and with access to clean water and appropriate sanitation for all. *Water Environ. Res.*, **81,** 809 (2009).

KEYWORDS: urban water management, resource recovery, decentralization, water reclamation and reuse.

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Introduction

The current "linear" approach to urban water management, which is sometimes called the *take, make, waste* approach in the sustainability literature when applied more broadly to natural resource use, is becoming increasingly unsustainable. The most obvious effect is growing water stress (insufficient water supplies) occurring broadly around the world, but concerns about resource consumption and the dispersion of nutrients into the aquatic environment also are growing. Urban water management utilities often lack the financial resources needed to provide adequate water supplies and waste management services. And, on a global basis, approximately 1 billion people lack access to clean water, and 2.5 billion lack access to appropriate sanitation. Thus, changes are needed to sustain urban water and resource management services.

Fortunately, a diverse toolkit is available and is increasingly being applied to reduce net urban water abstraction from the environment, thereby relieving urban water stress and reducing resource consumption and nutrient dispersal. This toolkit includes stormwater management/rainwater harvesting, water conservation, water reclamation and reuse, energy management, nutrient recovery, and source separation. These tools can be implemented in centralized and decentralized configurations. This paper will illustrate how these tools can be incorporated into higher performing urban water and resource management systems and, most importantly, it will discuss some of the key factors to allow these systems to be implemented.

Evolving Urban Water and Resource Management Requirements

Why Must We Change? This is a good question. Change is hard, and it creates distractions and consumes resources. Thus, there must be a good reason to change. The simple answer is that population growth and an increasing standard of living are pushing human use of our natural resources (including water) beyond sustainable limits (Wallace, 2005). Increased urbanization is further concentrating these non-sustainable consumption patterns (National Research Council, 2003). Natural resources (including water) are used in a linear "take, make, waste" pattern, which is the root cause for the current unsustainable resource consumption. For the water sector, this is leading to water stress, unsustainable resource consumption (energy and chemicals), the unsustainable dispersion of nutrients into the aquatic environment (especially phosphorus), and to financially unstable utilities. Currently, only a small fraction of the world's population lives under conditions of water stress, but this is estimated to grow to 45% by 2025, even without considering the effects of global climate change (Daigger, 2007b; World Resources Institute, 1996). Global climate change will further exacerbate this, as precipitation patterns become more variable and also create systematic effects, such as reduced snowpack and earlier snowmelts.

This evolving situation is surprising to many water managers, because of the historic success of the traditional urban water management system. Thought by some to be an invention of the industrial revolution, even ancient cities used the traditional approach of locating a pristine water source remote from the urban area, conveying it (often by gravity in ancient times, sometimes with pumps in the modern age) to the urban area, using it once, and then using the water flow to remove wastes and transport them for remote disposal. We are all familiar with the dramatic effect on public health resulting from the provision of clean water and the removal of waste from urban areas. In fact, this has been hailed as the single greatest contribution to public health over the past 150 years (British Medical Journal, 2007). The U.S. National Academy of Engineering (Washington, D.C.) recently recognized modern water and wastewater systems as one of the great achievements of the 20th century (Constable and Somerville, 2003). Treatment (both water and wastewater) was added as population growth resulted in fewer sources of pristine water and wastewater discharges adversely affected available water resources. However, given the outstanding success of this "linear" approach, why should we change? The answer is that population growth, an increased standard of living, and urbanization are leading to water stress, excessive resource consumption, and nutrient dispersal, as discussed above.

The development of resource constraints (including water) is not surprising when one considers population growth occurring over the 20th century and expected in the 21st century. Figure 1 presents the historical and projected global population beginning in 1800 and continuing through 2050, as developed by the United Nations (2005). Preceding this, the global human population is estimated to have increased from 150 million to nearly 1 billion between 0 and 1800 AD (850 million people over 1800 years). The population increased from approximately 1 billion to approximately 1.65 billion during the 19th century, and from 1.65 billion to approximately 2.5 billion during the first half of the 20th century. In the second half of the 20th century, the population more than doubled, from approximately 2.5 billion to over 6 billion. The question is whether this rapid population growth will continue, or whether it will moderate and reach a plateau. As illustrated in Figure 1, median demographic projections by the United Nations suggest a diminishing rate of global population growth, reaching approximately 9 billion by 2050. It is further estimated that a population plateau of approximately 10 billion will be reached and then sustained through the second half of the 21st century. Approximately 1 billion of the planet's current 6 billion people live in developed countries, and this is expected to remain approximately the same through the 21st century. Thus, essentially all of the population growth expected during the 21st century will occur in developing countries. It also is expected that living standards will improve in the developing countries—in fact, this is necessary, as it will be a major factor leading to the moderation of birth rates in these countries. The net result is that, if current trends do not change, population growth and increased consumption will increase the current use of the resources of 1 planet earth to approximately 3 planet earths, which of course is not sustainable. Environmental impact (I) often is expressed as the product of population (P) × affluence (A) × technology (T), as follows:

$$I = P \times A \times T \tag{1}$$

Applying this concept to the above discussion indicates that technology must be used to compensate for the growing adverse environmental impact of increased population and affluence.

Those of us living in the United States may be tempted to think that this challenge is for others to address. Irrespective of arguments based on moral and ethical grounds, from a practical perspective, we must embrace and act upon this challenge. There are several reasons for this. First, contrary to trends in other developed countries, the United States population is expected to increase by approximately 50%, from its current value of approximately 300 million, to approximately 450 million over the same 50-year period (from 2000 to 2050). Population growth in the United States will be compensated for by population declines in other developed countries (e.g., Japan, where the population has already begun to decline, and Western Europe), leading to the stable developed country population discussed above. Second, many areas of the United States currently are experiencing water stress, and this will increase dramatically over this same period (U.S. Department of Interior, 2005). Finally, we live in a global world, and events occurring outside of the United States increasingly are affecting us. Thus, it is not only necessary, but also in our best interests, to address growing water management needs, both in the United States and abroad. We must learn how to provide urban water and resource management services that provide a modern standard of living with reduced net resource consumption for a significantly greater number of people.

Perhaps the most significant change expected to occur during the first half of the 21st century is urbanization, which has been occurring for some time, but will become manifest in the 21st century (National Research Council, 2003). We have become an urban population, and this increasingly will be the case as the human population grows in the first half of the 21st century. Essentially all of the population growth occurring during the 21st century will be in urban areas. This may occur for a simple reason; the rural population has reached saturation values and may decrease as fewer people are needed per unit of production in agriculture. In fact, for the first time in human history, more than half of the human population is living in urban areas (National Research Council, 2003). The number of cities is increasing rapidly; they are increasingly being located in developing countries; and cities are becoming larger. This is illustrated by the historical data and projections presented in Table 1, where high income countries generally represent developed countries, while middle and low income countries represent developing and underdeveloped countries.

How Must Urban Water and Resource Management Systems Change? Stated differently, what problem are we trying to solve? The dramatic changes described above will result in equally dramatic changes in many aspects of life, including

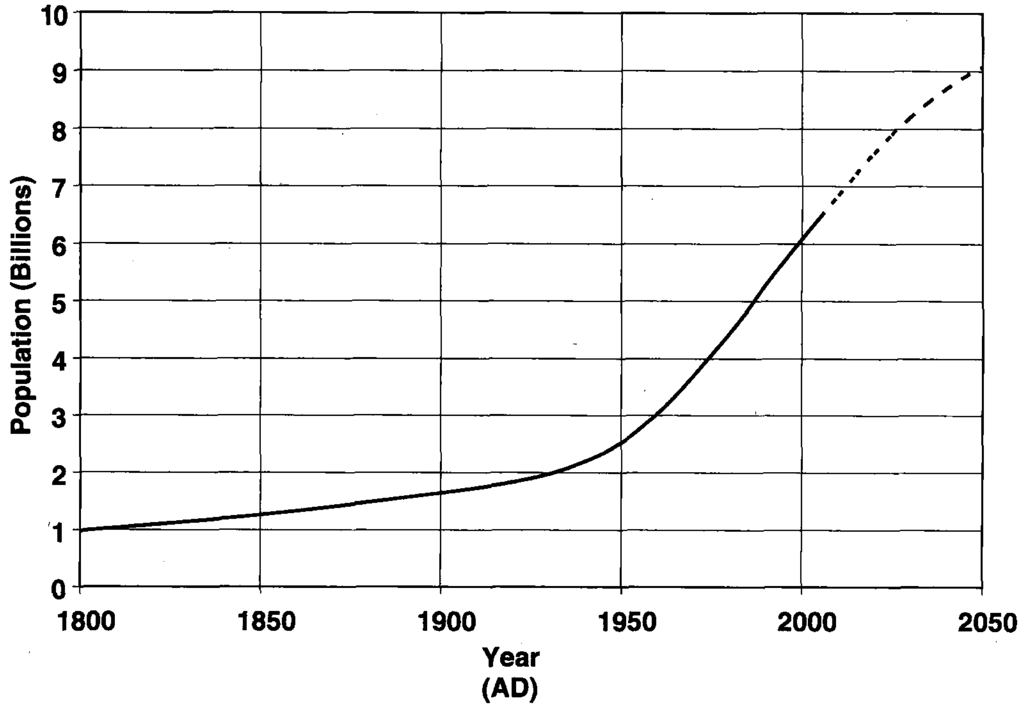

Figure 1—Historical (solid line) and projected (dotted line) global population projections per the United Nations (2005).

water management. Sustainable infrastructure and management authorities must be developed that will

(1) Dramatically reduce net water withdrawals for urban uses;
(2) Reduce water supply and waste management resource consumption (energy and chemicals), with a goal of energy neutrality; and
(3) Significantly improve nutrient management.

Access to sustainable water and sanitation for all also must be achieved to meet the established Millennium Development Goals. Because the existing and future situation is not the same in all locations, the response to achieve these goals also will not be the same. To understand some of these differences, it is useful to consider the following four country types, which differ in terms of population growth and changes in standard of living (all are affected by increased urbanization):

(1) Developed countries with a constant or declining population;
(2) Developed countries with a growing population;
(3) Developing countries (growing population) where living standards will increase; and
(4) Underdeveloped countries (growing population, but little change in standard of living).

Japan and many European countries represent the first type, while the United States is an example of the second. The developing countries of Asia (including India), Central and Eastern Europe, and Latin America represent the third type, while many countries in Africa represent the fourth. While the focus of this paper is on urban settings, it also is useful to discuss water management in rural settings. Rural needs often have dominated concerns in developing and underdeveloped countries because of the historical dominance of rural populations and because, in most countries (including the United States), agricultural water use, which is associated with the rural population, greatly exceeds domestic consumption.

Table 2 summarizes the existing water-management situation and changes needed in the political settings listed above, for both the urban and rural populations. Water management practices are well-established in both urban and rural areas of most developed countries with constant or declining populations. The principal issue is the sustainability of these approaches, both the ability to financially and physically sustain the required infrastructure and the associated environmental effects. Significant concern exists by some regarding the energy required by this approach and especially the failure to recover and recycle nutrients. The situation in developed countries with growing populations is similar, except that the needs of a growing population must be met. As illustrated in countries such as the United States, Australia, and Singapore, growing water needs can be met, even though sufficient water supplies do not exist based on current approaches and/or existing supplies are being adversely affected by global climate change. Water utilities are increasingly using

Table 1—Development of cities through the late 20th and early 21st century (National Research Council, 2003).

	Number of cities in each category			
Item	**1950**	**1975**	**2000**	**2015**
Cities with population of 1 million or more				
High-income countries	43	73	90	105
Middle- and low-income countries	40	122	297	449
Cities with population of 5 million or more				
High-income countries	5	9	9	10
Middle- and low-income countries	3	12	30	47

Table 2—Existing water-management situation and changes needed in various political settings.

Country type	Urban	Rural
Developed, constant or declining population	Generally traditional centralized water supply and wastewater management systems, which provide adequate service but are increasingly judged not to be sustainable. Significant improvements needed to reduce net water consumption, reduce energy, and recover nutrients.	Water supply generally by groundwater and wastewater management by soil-based systems. Enhanced community and on-site systems adopted in some instances. No changes needed.
Developed, growing population	Generally traditional centralized water supply and wastewater management systems, which provide adequate service but are increasingly judged not to be sustainable. Significant water supply problems in areas with growing populations, which are driving increased use of novel water supply approaches, such as water reclamation and reuse.	Water supply generally by groundwater and wastewater management by soil-based systems. Enhanced community and on-site systems adopted, in some instances. Trend to adopt this model in suburban locations.
Developing	Water provided by public water supply generally not considered to meet potable water standards and often not available in poorer sections. Wastewater collection often is present in more affluent areas, but is absent in poorer sections. Significant efforts to install centralized systems in more rapidly developing urban locations.	Water supply and waste management often by traditional means. Significant number of residents lack access to safe water and appropriate sanitation.
Underdeveloped	Water provided by public water supply generally not considered to meet potable water standards and often not available in poorer sections. Wastewater collection often is present in more affluent areas, but is absent in poorer sections. Little progress being made to improve water supply and sanitation.	Water supply and waste management often by traditional means. Significant number of residents lack access to safe water and appropriate sanitation.

poorer quality compromised water supplies and adopting nontraditional water supply options, such as water reclamation and reuse and desalination. Interest in decentralized systems also is developing in suburban locations, especially to reduce initial and long-term costs, but also to encourage water reclamation and reuse.

The present situation in developing and underdeveloped countries generally is similar. The principal difference is that water supply and sanitation are being extended in developing countries at a much greater rate than in underdeveloped countries. Centralized systems generally are being implemented in both types of countries, although decentralized systems are receiving increased attention.

Water and wastewater utilities are under significant cost pressures in all four country types and in both urban and rural locations. This occurs for many reasons, which clearly do not include a lack of willingness to pay. Urban dwellers will purchase bottled water at a unit price that is several orders of magnitude greater than the cost of water delivered to the tap, and water purchases from tanker trucks and other private delivery methods are much more expensive than centralized delivery. People will pay for water because it is essential for life. In spite of this, insufficient funding adversely affects the operation of many water and wastewater utilities, in both developed and developing countries. A lack of trust in water and wastewater utilities is one potential reason for this poor funding. Clearly, however, changes are necessary, to ensure the financial sustainability of urban water management utilities.

It is clear that change is necessary to accommodate the desirable global future of approximately 10 billion people on planet earth, with a much higher proportion living a higher standard of living and with net resource consumption less than current levels. The necessary changes in urban water and resource management to achieve greater sustainability can be expressed in terms of the proposed "triple bottom line" presented in Table 3.

The ability of alternate systems to achieve these goals is addressed below.

Toolkit to Achieve Greater Sustainability

Now that we know what must be achieved, the question is how. Fortunately, approaches are evolving that offer the promise to deliver much higher performance. They include

(1) Stormwater management and rainwater harvesting,
(2) Water conservation,
(3) Water reclamation and reuse,
(4) Energy management,
(5) Nutrient recovery, and
(6) Source separation.

These approaches can be deployed in a centralized or decentralized fashion. Some of these approaches are well-established and well-known, while others were introduced more recently and are evolving. Table 4 summarizes the six approaches, along with a comments on how these six elements contribute to improved sustainability (i.e., achievement of the goals listed in Table 3). Stormwater management, water conservation, and water reclamation and reuse can be combined under the term *water management.*

These toolkit elements can be implemented in a variety of configurations, ranging from centralized to decentralized (Daigger and Crawford, 2007). In a centralized system, potable water is produced in one, or a small number of, water treatment plants and distributed uniformly throughout the subject service area. Wastewater is collected and conveyed to one, or a small number of, wastewater treatment plants (WWTPs) for treatment and disposal or reuse. In contrast, in distributed systems, multiple potable and wastewater treatment facilities are provided through-

Table 3—Proposed triple bottom line urban water and resource management sustainability goals.

Sustainability area	Goal
Economic	• Financially stable utilities with the ability to maintain their infrastructure.
Environmental	• Locally sustainable water supply (recharge exceeds net withdrawal). • Energy neutral (or positive if possible), with minimal chemical consumption. • Responsible nutrient management, which minimizes dispersal to the aquatic environment.
Social	• Provide access to clean water and appropriate sanitation for all.

out the service area. A hybrid configuration consists of centralized and decentralized components. As illustrated in Table 5, various toolkit elements are best deployed in either centralized or decentralized/hybrid configurations.

Water Management. Stormwater management and rainwater harvesting represent a diverse set of technologies generally intended to capture stormwater runoff and treat it for introduction to the environment or capture it for later use (Daigger, 2008). These approaches also slow stormwater flow, thereby reducing peak flows to moderate flooding. System components generally are distributed throughout the urban area and, consequently, also are referred to as *distributed* or *decentralized stormwater management.* Their increasing popularity is illustrated by several papers presented in a recent edition of *Water Environment & Technology* (Hyland and Zuravnsky, 2008; Kennedy et al., 2008). The potential benefit of this approach, from a water-supply perspective, is illustrated by a simple calculation of the captured precipitation and the per-capita water supply that it can provide for various population densities, as presented in Figure 2. Stormwater capture offers significant potential to contribute to urban water supply in locations with modest population densities, or even in densely populated areas with high precipitation. For example, infiltrated stormwater recharging the groundwater can serve as a source of water for irrigation and other non-potable uses during dry periods. Stormwater management and rainwater harvesting are inherently applicable to decentralized and hybrid configurations. Rainwater is collected for use and/or reintroduced to the local environment.

Table 4—Toolkit to achieve increase urban water and waste management sustainability.

Item	Description	Example technologies	Contribution to sustainability
Stormwater management and rainwater harvesting	A diverse set of technologies intended to capture stormwater runoff, slow its flow to allow natural treatment processes to remove pollutants, reduce peak flow to moderate flooding, and infiltrate a portion into the groundwater or allow evapotranspiration by vegetation to later return it to the atmosphere (Strecker et al., 2005).	Permeable pavements, green roofs, rain gardens, bioretention basins; also known as *low-impact development.*	Local potable and non-potable water supply; pollutant removal to protect water resources.
Water conservation	The application of technologies that provide expected service with reduced water use, potentially coupled with behavior changes.	Low-flow shower heads, toilets, and washing machines; drip irrigation.	Significant reduction in water use.
Water reclamation and reuse	The treatment of wastewater (reclamation) for subsequent use as a water supply (reuse).	Wide variety, depending on wastewater and reclaimed water quality requirements.	Agricultural, industrial, irrigation, domestic (potable and non-potable) water supply.
Energy management	Conversion of the chemical energy in the organic matter and reduced nitrogen contained in wastewater into thermal, electrical, or mechanical energy; thermal transfer to/from treated effluent; application of energy-efficient approaches.	Anaerobic treatment; thermal combustion with energy recovery; microbial fuel cells.	Reduced energy required for treatment and/or energy recovery.
Nutrient recovery	The production of products from wastewater that can be used as fertilizers because of their nutrient value.	Land application of biosolids; struvite precipitation.	Reuse of nutrients reduces withdrawal from the environment.
Source separation	Separate collection of a various human waste sources reflecting their different characteristics and potential uses.	Grey water, black water, and yellow water.	Enables approaches that use less energy and/or improve nutrient recovery.

Table 5—Application of toolkit elements at centralized and decentralized scales.

Toolkit element	Centralized systems	Decentralized/hybrid systems
Stormwater management and rainwater harvesting	–	Permeable pavements, green roofs, rain gardens, etc.
Water conservation	New technologies and behavior changes	
Water reclamation and reuse	Treatment for potable use and reuse (direct and indirect)	Treatment for potable use and non-potable reuse
Energy management	Anaerobic digestion, combustion, microbial fuel cells	Capture heat energy, microbial fuel cells
Nutrient recovery	Land application of biosolids, struvite recovery	–
Source separation	Treatment of kitchen, black, and yellow wastewater	Supply potable and non-potable; treatment of kitchen, black, and yellow wastewater

Water conservation also is a well-established practice and involves a combination of technologies and practices. While behavioral changes are encouraged and welcomed, the emphasis here is on the use of technologies that result in reduced water use. A wide variety of approaches are available and are increasingly being applied, as evidenced by the recent May 2008 issue of the *Journal of the American Water Works Association* (Chesnutt et al., 2008; Hoffman, 2008; Maddaus et al., 2008; Mayer et al., 2008; Pape, 2008; Smith, 2008). Anecdotal evidence also suggests reduced domestic water use and the corresponding increase in wastewater strength (because per-capita domestic waste loads are independent of water use, reduced water use leaves less wastewater flow to dilute the waste mass). Water conservation not only benefits water supply and treatment, by reducing the quantity of water required, but also wastewater treatment, as a result of reduced wastewater volumes (Paulsen et al., 2007). Reduced water and wastewater flows extend the life of conveyance and treatment facilities, which can contribute to the financial sustainability of water and wastewater utilities, as long as reduced flows do not adversely affect revenues needed to operate these utilities. Water conservation benefits an urban water management system of any configuration, but they are inherently applied on a local (decentralized) basis.

Water reclamation and reuse is an established practice, which can dramatically reduce net withdrawal from the environment. Municipal water reclamation and reuse is practiced widely in water-short locations, to meet agricultural, industrial, thermal energy, and urban irrigation water needs. Even though it is well-developed, domestic water reuse (non-potable and potable) is less consistently practiced, for a number of reasons, including concerns about public perception and the assessment that such uses are to be implemented only under the most unusual circumstances. The perception also exists that this practice requires an unusually high level of treatment. Two factors are altering these perceptions.

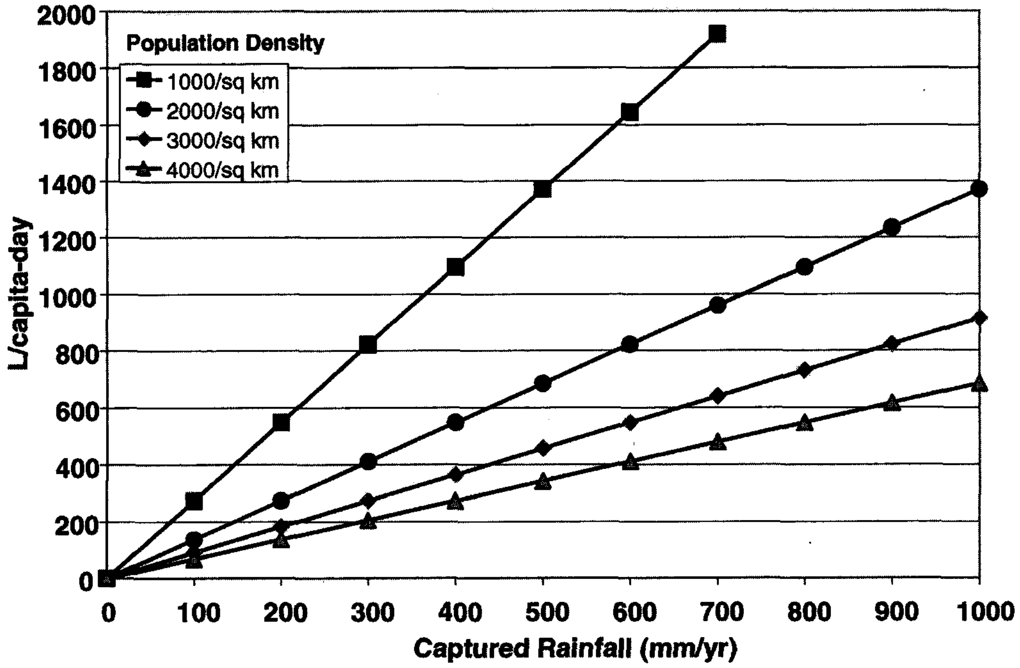

Figure 2—Water supply provided by capture of local rainfall as a function of population density.

(1) The growing number of successful examples, which are demonstrating that public perception may no longer be the implementation barrier that it once was and which also provide practical experience that facilitates successful implementation on subsequent projects; and
(2) The continuing evolution of cost-effective treatment technology that is capable of previously unknown performance levels, especially membrane technology (DiGiano et al., 2004).

Increasingly stringent discharge standards also are enabling reclamation and reuse, as the incremental cost for water reclamation is reduced compared with treatment and discharge options. While municipal water reclamation and reuse for agricultural, industrial, thermal energy, and urban irrigation uses reduce net water consumption, domestic non-potable and potable water reclamation and reuse can provide dramatic reductions in net domestic water use and significantly extend available urban water supplies. The more widespread adoption of this practice, coupled with water conservation, can lead to dramatic reductions in net urban water usage.

Water reclamation and reuse systems can be used to meet potable and non-potable uses and can be deployed in a centralized or a decentralized configuration. Although other configurations are possible, centralized systems may be more compatible with potable reuse, and decentralized systems may be more compatible with non-potable reuse. In a centralized system, wastewater is collected and treated to potable standards. For indirect potable reuse, it is introduced to a water supply source, such as a water supply reservoir or groundwater aquifer, whereas, for direct potable reuse, it is introduced directly to the water distribution system. Indirect potable reuse systems generally have gained the greatest favor, as they provide increased public health protection, as a result of the further attenuation of contaminants that occurs in natural systems, and because a more uniform blend of raw and reclaimed water is provided to the customer. This approach requires a high level of treatment, but only one water distribution system (for potable water).

In a decentralized system, water reclamation facilities are located strategically throughout the urban area where relevant demand exists. Wastewater is removed from an adjacent wastewater collection system in quantities needed to meet the subject water demand, treated to the necessary quality, and distributed to the customer. Residuals from the water reclamation facility can subsequently be discharged back to the wastewater collection system and conveyed to the downstream centralized treatment facility. This approach, often referred to as *sewer mining* or *scalping*, reduces wastewater conveyance costs and, although a dual distribution system is needed within the system service area, it is much less extensive than if a dual distribution system is used throughout the entire urban area. The principal cost burden associated with this approach is the loss of economy of scale with decentralized wastewater treatment. Traditionally, the capital and operation and maintenance costs for several smaller WWTPs were found to be significantly higher than those for a single, larger WWTP. Concerns also have existed about the reliability of remote treatment facilities (the ability to reliably produce the necessary product water quality). Both concerns have been mitigated by the development of new technology, especially membrane technology (Daigger, 2003; DiGiano et al., 2004). More recently, this concept has been extended to an even smaller scale, with systems (especially membrane bioreactors) used to reclaim water for non-potable uses in residential and commercial buildings (Daigger et al., 2005).

Energy Management. Increased water and wastewater treatment has resulted in increased energy consumption. The associated increased costs are a concern to many rate payers, while the negative environmental effets of increased energy consumption are of concern to others. Thus, significant desire exists to develop approaches with reduced energy and resource consumption. To place these concerns in perspective, consider United States electrical energy use for urban water treatment, distribution, and wastewater management, which is estimated to be 17.5 W/person (Carns, 2007). Compare this with the average per capita total United States electrical energy consumption of 1450 W/person (based on total United States energy consumption in 2006 of 3817 billion kW-h/y [U.S. DOE EIA, 2009] and a total population of 300 000 000). Water often is reported to consume approximately 2% of total United States electrical energy consumption. If an allowance for the energy required to supply water resources is added to the 17.5 W/person for water treatment and distribution and wastewater management provided by Carns (2007), it appears that this common perception is reasonable. These data illustrate that water conservation, as discussed above, represents one of the easiest methods to reduce the energy consumption associated with water use.

Further segregation of the Carns (2007) data in Figure 3 illustrates the significant role of pumping to distribute potable water. This suggests that the energy consumption associated with increased treatment often required for water reclamation and reuse may be more than offset by reduced energy requirements for water supply, treatment, and distribution, potentially offering a net reduction in energy use. Potential energy savings will be system-specific and will require site-specific analysis. For example, it is estimated that approximately 7% of the total energy use in the State of California is simply to transport water from Northern to Southern California—an energy use that can be reduced significantly through water reclamation and reuse. These considerations illustrate that systematic analysis of urban water management systems, including water supply, water and wastewater treatment, and conveyance, can result in water-supply approaches that inherently require less energy.

Energy present in the wastewater stream, which consists of heat energy and the energy value of organic matter and nitrogen present resulting from pollutant discharges, also can serve as an energy source. Heat energy may be thought to be present, at least partially, as a result of the heat added to the wastewater through use and can be related to per-capita wastewater production, as illustrated in Figure 4. The energy value for organic matter is presented in Table 6. These values represent maximums that are not practically achievable. For example, only approximately 30 to 40% of the energy present in biogas is converted to electrical energy in combined heat and power (CHP) applications, and the capture and use of heat energy will increase the overall efficiency to just over 50%. To illustrate the potential, however, consider treatment of wastewater in an anaerobic system with a treatment efficiency of 80%, yielding biogas with an energy content of 17.4 × 0.8 or 13.9 W/person. If this biogas is captured and converted to electrical energy using a system achieving an efficiency of 35%, 4.9 W/person of electrical energy could be produced, and over 7 W/person of useful energy would be produced if heat energy also is captured.

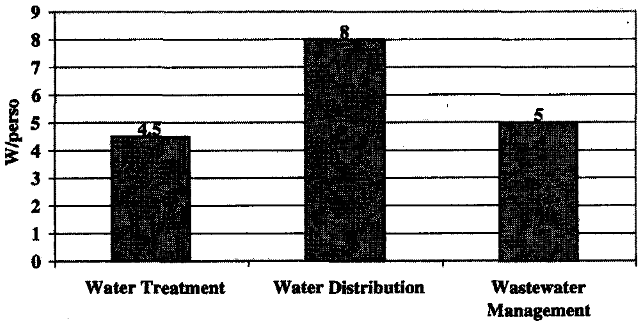

Figure 3—Energy requirements for water treatment, water distribution, and wastewater management (Carns, 2007).

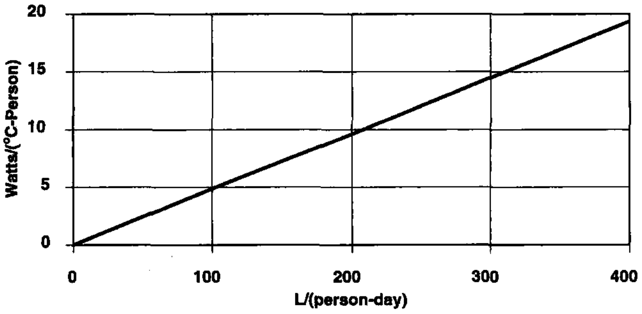

Figure 4—Thermal energy available in (waste)water stream. Based on 70 (W·min)/(°C·L), equal to 4200 J/(°C·L).

Table 7 summarizes technologies that potentially can use the organic matter and/or nitrogen content of wastewater to produce energy, the proportion of wastewater constituents that they use to produce energy (feedstock), and constraints on the conversion of these feedstocks to energy.

The following three types of technologies generally are available:

(1) Anaerobic biological technology, which converts organic matter to biogas;
(2) Thermal technologies, which combust (particulate) organic matter and extract thermal energy; and
(3) Microbial fuel cells.

Anaerobic treatment can be applied directly to wastewater or to the sludges produced as a result of wastewater treatment. An important constraint for the direct anaerobic treatment of wastewater is the relatively high solubility of methane in water, which results in a significant loss in the treated effluent for dilute feed streams. This loss is environmentally significant, because the global warming potential of methane is 23 times that of carbon dioxide. The hydrolysis of particulate organic matter is a constraint for both direct anaerobic treatment of wastewater and sludge treatment. This constraint can be mitigated by biological, physical, and/or chemical pretreatment, to hydrolyze particulate organic matter (particularly biological cells) before anaerobic treatment (Roxburgh et al., 2006). An important constraint for all anaerobic treatment systems is the conversion of biogas to useful energy, as discussed above.

Thermal processes generally use particulate organic matter that is present in the influent wastewater or produced as a result of wastewater treatment. Their efficiency is constrained by the removal of water before thermal processing, as it must be evaporated in the thermal treatment process, which reduces the net energy available. Microbial fuel cells offer the potential to extract energy from biodegradable organic matter. Constraints include the hydrolysis of particulate matter (which often is limited in biofilm systems) and the efficiency of conversion of liberated electrons to useful energy (which often is on the order of 20% with current devices; Logan et al., 2006).

Energy-management technologies often are best implemented on a more centralized scale, as a result of the economies of scale. For example, a relatively small CHP system would have an electrical output of 100 kW. Calculations presented previously in this paper indicate that approximately 4 to 5 W/person of electrical energy can be produced from the biogas produced by direct anaerobic treatment of wastewater. Thus, the wastes from 25 000 people must be aggregated to provide the organic matter necessary to power such a system. The development of microbial fuel cells is still in its infancy and, consequently, their optimum size range is not yet defined. In contrast, the use of the thermal energy in the wastewater stream would inherently be implemented on a distributed basis as the uses for the thermal energy are distributed.

Table 6—Energy available from pollutants contained in wastewater in W/person.[1]

	Garbage grinders	
Fraction of wastewater constituents included in calculation	**Without[2]**	**With[3]**
Biodegradable chemical oxygen demand (COD)[4]	17.4	21.8
Biodegradable COD[4] + total Kjeldahl nitrogen (TKN)[5]	27.4	31.1
Total COD[6]	25.5	31.9
Total COD[6] + TKN[5]	35.5	41.9

[1] Based on 0.145 (W·d)/g oxygen demand converted to energy. Computed from methane equivalent of COD (0.35 m^3/g COD) using methane energy equivalent of 35 800 kJ/m^3 and recognizing that 1 J = 1 (W·sec).

[2] 80 g 5-day biochemical oxygen demand (BOD_5)/(person·d).

[3] 100 g BOD_5/(person·d).

[4] 1.5 g biodegradable COD/g BOD_5.

[5] 15 g TKN/(person·d), 4.6 g O_2/g TKN.

[6] 2.2 g COD/g BOD_5.

Table 7—Energy recovery options.

Option	Feedstock	Constraints
Anaerobic treatment		
Direct	Biodegradable organic matter	• Organic matter conversion efficiency • Loss of methane in treated effluent resulting from solubility • Hydrolysis of particulate organic matter • Conversion of biogas to energy
Sludge	Settleable biodegradable organic matter in wastewater plus biodegradable fraction of biomass produced in downstream biological treatment	• Organic matter conversion efficiency • Hydrolysis of particulate organic matter • Conversion of biogas to energy
Sludge (staged, pre-treated)	Settleable biodegradable organic matter in wastewater plus biomass produced in downstream biological treatment	• Organic matter conversion efficiency • Conversion of biogas to energy
Thermal	Particulate organic matter in wastewater plus biomass produced in downstream biological treatment	• Proportion of water that must be evaporated compared with organic matter, which can be combusted • Efficiency of use of thermal energy
Combined thermal/ biological	Particulate organic matter in wastewater plus biomass produced in downstream biological treatment	• Constraints of thermal and biological systems applied
Microbial fuel cells	Biodegradable organic matter (current application and nitrogen (future potential)	• Hydrolysis of particulate organic matter and nitrogen • Efficiency of conversion of liberated electrons to useful energy

Nutrient Recovery. Wastewater management systems are links in global nutrient cycles, as a portion of the nutrients applied to grow crops for human consumption ultimately ends up in the wastewater stream. The historical practice of land application of wastewater to crop lands and the current practice of the reuse of municipal biosolids in agriculture recycles these nutrients. Unless nutrient removal and accumulation in the biosolids is essentially complete, biosolids recycling still allows significant dispersion of nutrients into the aquatic environment. Nitrogen removal from the liquid stream, as currently practiced, generally involves nitrification and denitrification, so that the removed nitrogen is returned into the atmosphere, largely as nitrogen gas (N_2). Only a small portion of the nitrogen applied to agricultural land actually ends up in the wastewater stream, so nitrogen recovery will do little to alter the global nitrogen cycle. Moreover, because nitrogen is removed from the atmosphere to produce commercial fertilizer, the return of nitrogen to the atmosphere through wastewater treatment does not interrupt this cycle. The principal benefit of applying nitrogen removal in the wastewater system is to prevent the harmful effects of discharging nitrogen compounds to the aquatic environment, recognizing that nitrification and denitrification will occur in the aquatic environment if not in the wastewater system. However, because commercial nitrogen fertilizer production is energy-intensive, nitrogen recovery from wastewater by a variety of techniques offers potential energy savings.

The situation with phosphorus is different. Because phosphorus is not returned to the atmosphere, its discharge to the aquatic environment results in net dispersion into the environment. Moreover, the supply of commercially available phosphorus, an element which is essential for life, is limited and may only last approximately 100 years at current consumption rates. It is surprising, but direct agricultural recycling through biosolids application is relatively ineffective, given current practice, which is to apply biosolids at agronomic rates based on nitrogen—not phosphorus—content. This was appropriate when phosphorus removal (chemical or biological) was not practiced in wastewater systems, as the nitrogen content then determines the allowable loading rate. The current cost-effectiveness of agricultural land application is based on the corresponding application rate. However, when phosphorus removal is practiced, the phosphorus content of the biosolids increases significantly, to the point where phosphorus determines the application rate and can make agricultural land application much less cost-effective and attractive. If chemical phosphorus removal is practiced, phosphorus becomes less available for crop production, thereby allowing biosolids to be applied at nitrogen-limiting rates. However, from the perspective of phosphorus, this represents disposal, rather than recycle and reuse. The phosphorus in the biosolids is readily available if biological phosphorus removal is practiced, but lower application rates must be used, thereby negatively affecting the economics of this practice. As a consequence, phosphate recovery from wastewater is needed to recycle this nutrient effectively.

Fortunately, technologies are available to not only remove phosphorus from the wastewater stream, but also to recover it in useful forms (Wilsenach et al., 2003; Woods et al., 1999). In general, phosphate can be recovered as calcium phosphate [$Ca_3(PO_4)_2$] or struvite ($MgNH_4PO_4$). Improvements continue to be made in the approaches and technologies used. While the economics currently are favorable only in certain circumstances (high biosolids disposal costs), as a result of the depressed cost of phosphate ore, interest in this approach is leading to increased applications, which are further advancing the technology. The mass of phosphorus in the wastewater stream has been reduced significantly in recent years, as a result of the ban on phosphate in home laundry detergents, and it can be further reduced through further bans for other products. Nevertheless, the wastewater stream still provides approximately 3 g of total phosphate as P/(person·d).

Table 8—Distribution of organic matter and nutrients in typical European wastewater (Henze and Ledin, 2001).

Source	BOD_5 (g/(person·d)	Total nitrogen (g-N/(person·d)	Total phosphorus (g-P/(person·d)	Potassium (g-P/(person·d)
Toilet waste				
Feces	20	1.1	0.6	1.1
Urine	5	11.0	1.4	2.5
Kitchen	30	0.8	0.3	0.4
Bath/laundry	5	1.1	0.3	0.4
Total	60	14.0	2.6	4.4

Although the appropriate scale for nutrient-recovery technologies has not been determined, it seems most likely to be more centralized than decentralized. Aggregation of the nutrients from many individuals may be necessary, to make the operation of a nutrient-recovery facility practical.

Source Separation. *Source separation* refers to the provision of multiple qualities of water for domestic and commercial use and the collection of separate wastewater streams with significantly different qualities. Dual distribution systems, which separately provide potable water and water for urban irrigation, are becoming common in water-short locations. Separation of uses requiring potable (i.e., for direct consumption and cooking) from non-potable (i.e., for toilet flushing and laundry) water within residential and commercial establishments also is being practiced in some instances. This allows different qualities of source water, with different levels of treatment, to supply these needs. The net result is that additional water supplies are made available to meet human needs.

Likewise, domestic and commercial wastewater sources can be separated, resulting in wastewater streams with significantly different qualities. Grey water, consisting of relatively uncontaminated water from sources such as laundry and bathing, represents a relatively large proportion of total domestic and commercial wastewater production. Kitchen waste represents a relatively small volume, but contains a high concentration of biodegradable organic matter. Black water is waste from the toilet and contains much of the organic matter, nutrients, and pathogens. Separation of this waste stream concentrates much of these pollutants in a relatively small volume, which can be used more effectively for energy production and nutrient recovery. Urine can be further separated from the toilet waste, as it is a small volume, and it contains the majority of the nutrients and a disproportionate fraction of hormones and pharmaceuticals in the domestic and commercial waste stream (Birkett and Lester, 2003). Separation of these waste sources can facilitate water reclamation and reuse, organic matter conversion to energy, and nutrient recovery, as is discussed below. Table 8 provides sample data on the distribution of organic matter and nutrient contributions by these various wastewater sources, illustrating the relatively low pollutant content of bath and laundry sources, organic matter content of kitchen wastes and feces, and relatively high proportion of nutrients contained in urine.

Source separation is applied inherently at a decentralized scale, as multiple piping systems are required, and the total length of piping is reduced if multiple treatment facilities are distributed throughout the service area.

Integrated Systems

The system elements described above must be incorporated to integrated systems to achieve their full potential. Systems can be developed to dramatically improve water management, by significantly reducing net water consumption. Organic matter management also can be altered to increase energy and nutrient-recovery performance.

Urban water management systems can incorporate water conservation, rainwater harvesting (including distributed stormwater management), and water reclamation and reuse to achieve significant reductions in net urban water consumption and the need to import water. Source separation can further enable water reclamation and reuse. Specific results and approaches vary, depending on the hydrologic setting, but it is clear that dramatic reductions in the need to import water can be achieved in many locations.

Modern systems can incorporate both centralized and decentralized elements. A centralized potable water distribution system is generally needed if surface water is imported into the urban area. As discussed above, this could be supplemented by a centralized wastewater reclamation and reuse system. The Upper Occoquan Sewage Authority (Centreville, Virginia) (UOSA) represents a long-standing (30-year) example, where a 205 000-m^3/d (54-mgd) indirect potable water reclamation plant supplements the water supply for Northern Virginia. UOSA provides source water protection and water supply reliability for this densely populated urban location. The Republic of Singapore offers a further example, which incorporates "four taps" to provide a reliable and robust water supply for this island nation. The "four taps" include the following:

(1) Supplies collected in both dedicated watersheds and as urban stormwater;
(2) Imported surface water from watersheds in Malaysia;
(3) Desalination; and
(4) Water reclamation and reuse, referred to as *NEWater*.

All four sources are used to produce potable water, which is distributed through a largely centralized water distribution system, and wastewater is collected and treated in conventional WWTPs. A portion of the treated effluent is discharged to the ocean, but an increasing proportion is reclaimed as NEWater and distributed to industry or reintroduced to the potable water supply (indirect potable reuse). Many industries value the higher quality of NEWater because of its lower total dissolved solids (TDS) content, resulting from the incorporation of reverse osmosis treatment. An aggressive public communication and water conservation program is helping to reduce water use. Stormwater and local water management also are being incorporated to water features that not only provide water quality improvement and augment water supplies, but also "showcase" water and create water-related recreation through a program called *ABC*, or *Active, Beautiful, and*

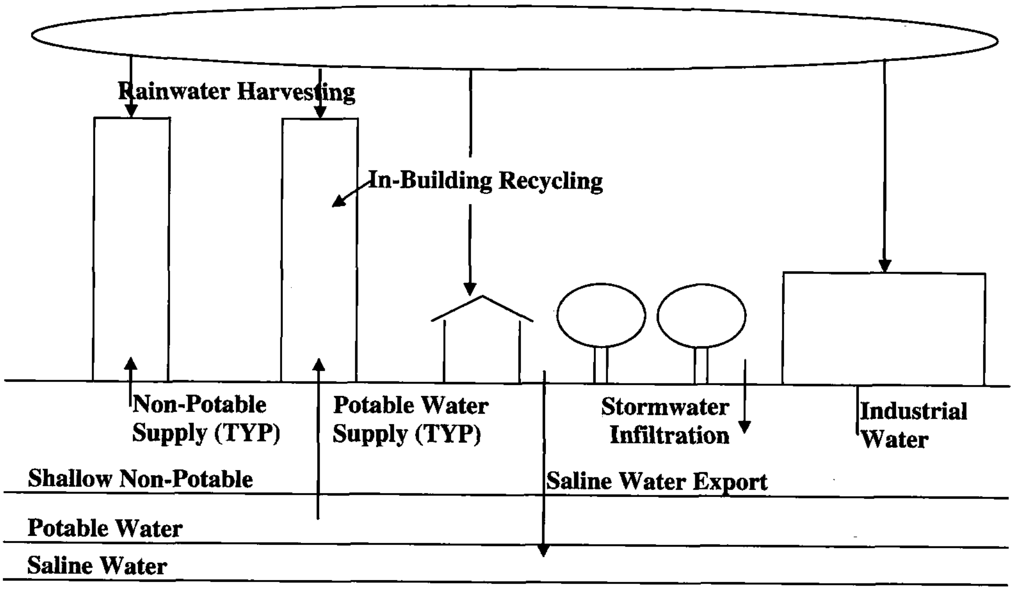

Figure 5—Example decentralized urban water management system (Daigger, 2008).

Clean. Although Singapore is located in a tropical setting with significant rainfall, the high population density for this island nation would create severe water shortages if only local water supplies were to be relied upon using traditional approaches. Imported water will be used as available, but the aggressive capture of local water resources coupled with water reclamation and reuse (NEWater) and desalination provides the Republic of Singapore with a reliable and robust water supply, even if imported water from Malaysia becomes unavailable in the future. While desalination is an important element of Singapore's future water supply, water reclamation and reuse is much more important, in terms of the total volume provided, as a result of the much lower cost and environmental burden associated with NEWater production resulting from much lower TDS concentrations. This approach provides a flexible portfolio of water supply options as the population increases from the current value of approximately 4.5 million to a projected future population of 7 million.

Others are incorporating decentralized elements to urban water management systems. "Sewer mining" or "scalping" has been used historically in locations like Southern California and is becoming common in many water-short locations to provide urban irrigation water. The extension of this concept to produce non-potable water for domestic purposes, such as toilet flushing and laundry, also is beginning to occur; the Solaire building in New York City represents a notable example. However, this practice can be extended significantly. Figure 5 provides an example of one such concept (Daigger, 2008), which makes maximum use of local water resources, including precipitation and local groundwater resources. Precipitation is captured through both rainwater harvesting and the infiltration of stormwater into shallow groundwater, which is used as a non-potable water supply. Non-potable water can also be provided through in-building recycling. The potable supply is provided by a potable water aquifer, which also could be recharged by locally collected water resources or imported water. Water withdrawn from the non-potable aquifer could be treated, if necessary, for a specific use. In addition to in-building recycling, locally generated wastewater can be treated for irrigation use, which will recharge the local, non-potable aquifer. It will be necessary, in a relatively closed system, such as this, to manage the overall system water and salt balances. The water balance can be managed by importing water or exporting stormwater/treated effluent, as necessary. The salt balance may be sufficiently managed by such exports, but excess salt also can be removed by reverse osmosis and discharged to a saline aquifer if necessary, which represents an improvement over the current practice of discharging these salts to fresh water. Alternately, brine-recovery technologies are evolving and can be applied. Potable water treatment can be provided on a localized basis, if needed. A system such as this would comply with the guiding principles and system constraints described by Daigger (2008) and discussed below.

While choices concerning alternate urban water management systems, and their relative advantages and disadvantages, are reasonably clear, this is not the case for wastewater organic matter management. Centralized organic matter management offers significant economies of scale, given technologies currently available, as discussed above. The necessary economy of scale would be achieved in a centralized system serving sizable urban areas, even if upstream "scalping" is provided, as described above, because the organic matter is sent to the centralized treatment facility. However, the necessary economy of scale may not be achieved in a fully decentralized system.

Source separation is a particularly interesting option to facilitate decentralized water management and centralized organic matter and nutrient management. Grey water could be processed on a distributed basis, while black water, kitchen waste, and yellow water could be conveyed to more central locations for efficient processing into energy and for nutrient recovery. The organic matter concentration in the black water waste stream would be increased significantly, because of the associated low water use, which facilitates direct anaerobic treatment. Combining black water with food waste would further increase the amount of organic matter available for conversion into energy, thereby increasing the benefit of this approach and also simplifying the collection and transport of this solid waste fraction. Revisions to existing conveyance-system practices may

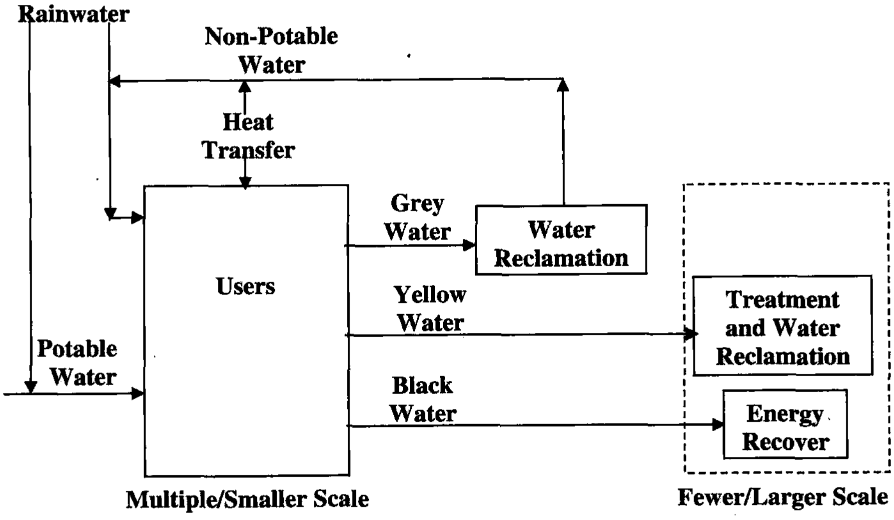

Figure 6—Example integrated urban water and resource management system.

be required to transport this more concentrated slurry. Further resource recovery could be achieved if yellow water is separated, especially as a source of phosphorus. Post-treatment (following anaerobic treatment) of black water also would be simplified, as the nutrient content of this waste stream would be reduced significantly. Distributed water management would facilitate heat energy recovery from (or rejection to) the wastewater stream, as segregation of less contaminated water streams will facilitate the application of the required heat extraction (or addition) technology, as a result of reduced fouling. Perhaps even more important would be reductions in energy requirements for water heating resulting from reduced water consumption. Reduced pumping for water distribution also will reduce energy requirements, as discussed above. Figure 6 provides a conceptual illustration of such a system. With such an approach, urban water requirements for domestic and commercial uses can be reduced to values approaching 50 L/(person·d) and energy neutrality for urban water management can be achieved, with significant recovery of phosphorus (and perhaps also nitrogen).

Figure 6 provides guidance to develop urban water, organic matter, and nutrient matter management options for specific urban areas. Specific alternatives then can be developed based on the guiding principles and constraints articulated by Daigger (2008), as presented in Table 9. These alternatives can then be evaluated using the approach outlined by Daigger and Crawford (2005) to find the most sustainable solution. It is clear that these options can meet the environmental goals for more sustainable urban water and waste management systems outlined in Table 2. The social goal of access by all to clean water and appropriate sanitation also is made more achievable by these approaches. However, can more stable utilities be developed? This question is addressed in the following section.

Implementing Advanced, Integrated Urban Water and Waste Management Systems

While systems with significantly improved performance capabilities are available and can be created, significant barriers exist to their implementation, as illustrated by the force field analysis presented in Figure 7. While centralized and elements of hybrid urban water management systems have been demonstrated, the integration of energy and nutrient recovery has not. Thus, the practicality, economics, and sustainability of these options are yet to be demonstrated. The need for full-scale trials is urgent. Another constraint is institutional in nature. Stormwater, water, and wastewater too often are managed by multiple utilities within urban areas (different political jurisdictions, stormwater versus water versus wastewater utilities). A further factor is the practice by the

Table 9—Guiding principles and constraints to formulate decentralized systems (Daigger, 2008).

Guiding principles	Constraints
1. Protect and subsequently use locally available water resources whenever possible.	1. Maintain water balance for both typical and extreme (wet and dry) conditions.
2. Mimic local hydrologic patterns before development; generally means infiltration of high-frequency, low-intensity storms and allowing high-intensity storms to create runoff.	2. Maintain long-term salt balance.
3. Public health is protected by incorporating multiple barriers, especially considering pathogens and trace contaminants.	3. Maintain nutrient balance.
4. Consider total resource consumption and potential for resource recovery when formulating systems.	4. Manage residuals, both over short and long time scales.

Figure 7—Force-field analysis for implementation of advanced integrated urban water and waste management systems.

water management profession of "stove piping" (i.e., separate and independent management) into the stormwater, water supply, and wastewater management professions, even when a single utility manages all three "waters". The urgency of the need to change often is hidden by the fact that the effects of population growth on the availability of water resources are manifested locally. This is being countered, to some extent, by growing realization of the potential effects of climate change on water supply issues, as illustrated by the recent drought in the Southeastern United States. Likewise, the emergence of greenhouse gas issues has highlighted resource .(energy) consumption by the water and wastewater industries and focused attention on their reduction. Thus, while the situation is beginning to change, the question that arises is how these constraints can be overcome.

First, the economics of alternate systems must be properly evaluated (Daigger, 2007a). As these approaches effectively create new water resources, the evaluation must consider the systematic effects on the entire water supply and wastewater management system, including water resources. Moreover, because their implementation will allow further expansion of the urban water management system to be avoided, or allow the most expensive to operate elements to be retired, evaluations must not be based on average costs, but on incremental costs. Consider the economics of water reclamation and reuse as an example. The cost of water reclamation and reuse should be compared with the most expensive water supply option, not the average cost of water, as it is the most expensive water supply option that will be avoided. This example demonstrates that a clear articulation of the incremental costs for any subject system will allow rapid screening of the economics of various options. Options that offset the highest incremental costs may be the most beneficial and should be targeted for more detailed evaluation.

Institutional barriers also must be addressed. Although the integration of urban water management utilities may be a step in this direction, it is not a necessary step. All that is truly required is cooperation between the relevant utilities. Experience further indicates that barriers created by the stove piping within the profession can prevent the systematic view and cooperation needed, even within a single, broadly responsible utility (Daigger, 2007b). Thus, changes within the urban water management profession appear to be the key barrier that must be overcome. Implementing such changes is within the control of the profession.

It also is perceived that the existing urban infrastructure represents a barrier to implementation of these potentially higher performing systems. Because urban areas have been built around the concept of a "one-use" approach to water, it is hypothesized that our systems cannot be converted. This preconceived notion neglects the fact that urban areas are expanding and also are subject to redevelopment (Daigger, 2007a). The successful implementation of water conservation measures throughout urban areas in the response to need is well-demonstrated and documented. The higher performing systems described above can be installed in areas of new development and can be retrofitted as redevelopment occurs. Such approaches can extend existing centralized system elements and, thereby, produce significant capital cost savings. Important examples of these beneficial economics exist around the world. Impact fees can fund these measures where they accommodate population growth, but system operating costs also must be funded, which generally will require increases in water (and wastewater) rates. Increasing rates will require utilities to communicate effectively with the affected public and to couple them with measures that can help individuals manage their total utility bill through subsidies. For example, incentives to adopt water conservation can reduce net consumption in the face of rising unit charges for water and allow consumers to maintain consistent water bills. Examples of such effective public communication programs also exist. If these factors can be addressed successfully, it appears likely that financially sustainable utilities with the ability to maintain their infrastructure will result.

Returning to the four scenarios described in Table 2, it may be said that, we, in developed countries with growing populations, are best positioned to embrace, develop, and implement improved approaches to urban water and resource management. We have the resources (human, technological, and financial) to do so and the need to serve growing populations. In so doing, we also will contribute to progress in the developing and underdeveloped countries, by creating more efficient and effective models that can be implemented there to meet the existing significant and growing need. One also may suspect that necessity will drive innovation, especially in developing countries. Our failure to seize the opportunity before us will negatively affect us, because we will have lost an opportunity to serve humankind more broadly and because of our loss of leadership in urban water and resource management. This leads to perhaps the greatest need, which is for integration within the urban water management profession. Our current stove piping into stormwater, water supply and treatment, and wastewater and biosolids management impedes the ability of many practicing professionals to see the overall picture and envision the possibilities for improved performance by more integrated systems. Wastewater professionals often refer to themselves as the "practical environmentalists" because of the historical contribution that wastewater treatment has made to improving and protecting public health and the environment. Increasingly, we are being called on to further enhance this contribution, while also reducing net resource consumption, including both water and energy. As true environmentalists, we need to understand the broader definition of this phrase, which is now possible given available technology and expected by the broader public. Our profession has risen to such challenges in the past, and it is up to us to do so now.

Conclusions

An urgent need exists to alter approaches to urban water management to

1. Supply water to a growing global population, which is becoming increasingly urbanized and with an increasing standard of living;
2. Accommodate increasing water scarcity exacerbated by global climate change;
3. Reduce resource consumption required to meet these needs; and
4. Reduce the dispersion of nutrients into the aquatic environment.

Approaches also are needed to increase the financial stability of urban water management utilities. Fortunately, new approaches are evolving, which offer the promise to deliver much higher performance, including the following:

1. Stormwater management and rainwater harvesting,
2. Water conservation,
3. Water reclamation and reuse,
4. Energy management,
5. Nutrient recovery, and
6. Source separation.

These approaches can be incorporated into urban water and resource management systems with improved performance characteristics, including significantly reduced urban water use, reduced energy consumption, and nutrient recovery. Centralized water reclamation and reuse systems and systems incorporating decentralized elements (hybrid systems) already have demonstrated the capability to significantly reduce net urban water consumption. Coupling hybrid or decentralized water management with source separation and centralized organic management and nutrient recovery offers the potential to achieve energy neutrality and significant nutrient recovery. Different qualities of urban water (potable, non-potable, and irrigation) would be supplied, and wastewater sources would be segregated to separate those streams containing a higher proportion of organic matter and nutrients from less contaminated wastewater sources will greatly facilitate water, energy, and nutrient recovery.

Guiding principles can help formulate alternative systems, which can be analyzed to determine those that are the most sustainable. Economic evaluations need to consider systematic effects and must be evaluated based on marginal reductions in urban water supply and wastewater management costs rather than average costs. These systems can be implemented within existing urban areas as development and redevelopment occurs. The greatest institutional barrier to implementation of improved systems probably is the stove piping of the urban water management profession, a situation that can be addressed. Developed countries with growing populations, such as the United States, offer significant potential to develop these systems. If we do not seize this opportunity, it is likely that developing countries will do so, as the need there is urgent.

Credits

This paper was presented as the Association of Environmental Engineering and Science Professors Lecture at the 81st Annual Water Environment Federation Technical Exhibition and Conference (WEFTEC), Chicago, Illinois, on October 20, 2008. It represents the culmination of nearly a decade of pursuing the topic of how our profession must adapt to the altered needs of the 21st century. The broader discussion the author has been participating in began in 2001, when he was the American Academy of Environmental Engineers (Annapolis, Maryland) (AAEE) Kappe Lecturer and offered a lecture entitled "The Wastewater Treatment Plant of the Future". It continued through numerous discussions, lectures, and publications, some of which are referenced in this paper. Involvement with a U.S. National Academy of Engineering (Washington, D.C.) initiative on urban sustainability, presentation of the American Society of Civil Engineers (Reston, Virginia) Simon W. Freese Lecture in 2006, and keynote/plenary lectures at the International Water Association (London, United Kingdom) Biennial Conference in Beijing (2006) and Leading Edge Water and Wastewater Treatment Technology Conference in Zurich (2008) represent further advances. During this time, the ideas presented in this paper have been challenged by and discussed with too many colleagues to mention. Their contributions are gratefully acknowledged. Comments by Jeremy Guest, currently a Ph.D. student in Civil and Environmental Engineering at the University of Michigan (Ann Arbor, Michigan), on this manuscript were particularly helpful and are gratefully acknowledged. Thanks to my wife Patty also for reading various versions and offering constructive criticism. While many have contributed to the thoughts and analysis presented in this manuscript, the opinions expressed here are solely those of the author, who takes full responsibility for them.

End Note

Anyone interested in the topic of sustainability should read the book *Collapse* by Jared Diamond (2005). The author analyzes several ancient societies, many of which were not sustainable (they collapsed), discusses the situation in a number of modern societies, and distills lessons for achieving sustainability. The bottom line is that sustainability is ultimately a societal choice. Those societies that remain true to their core principles, but continue to adapt their practices to practical realities survive (are sustainable), but those that confuse practices with core principles and continue those practices after they are no longer applicable collapse (are not sustainable). This should serve as a lesson, not only to our society, but also to our profession. The current one-use approach to urban water management has created enormous human health and economic benefits for the human population—an accomplishment for which our profession is rightfully proud. Modern water and sanitation systems have been recognized as one of the 20 greatest engineering achievements of the 20th century (Constable and Somerville, 2003). Having achieved this in the 20th century, the question is how will our profession adapt to the altered circumstances of the 21st century? Following Diamond's advice, we will do this by adapting our practices, while remaining true to our core principles. This paper has been about how we can adapt our practices. The author would suggest that the core principles of our profession, as demonstrated by the actions of our forefathers, include a dedication to public service, an appetite to adopt beneficial innovations, and persistence in pursuing paths that will accomplish the above. Our profession will be sustained if we remain true to these principles and adapt our practices to the changing situation in the 21st century.

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