AEESP LECTURE

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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 traditional linear “take, make, waste” approach to managing water is increasingly 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 conservations along with 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 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.

KEYWORDS

Urban Water Management, Resource Recovery, Decentralization, Water Reclamation and Reuse

INTRODUCTION

The current “linear” approach to urban water management, which is sometimes called the “take,
The "take, make, waste" approach in the sustainability literature when applied more broadly to natural resource use, is becoming increasingly unsustainable. The most obvious impact 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 are also growing. Urban water management utilities often lack the financial resources needed to provide adequate water supply and waste management service. And, of course, on a global basis about 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 further 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, 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 (NRC, 2003). Natural resources (including water) are utilized 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. It is estimated that the human population is currently consuming more resources than the planet can provide based on current consumption patterns. Global climate change, which has received so much recent attention, is but one indication that current behavior patterns cannot continue without severe consequences for humankind. Recent analyses also demonstrate that water management approaches are not sustainable. Currently only a small fraction of the world’s population lives under conditions of water stress, but this is estimated to grow to 45 percent by 2025, even without considering the impacts of global climate change (Daigger, 2007b; World Resource 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 result is surprising to many water managers due to 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 impact 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 (BMJ, 2007). The United States (U.S.) National Academy of Engineering 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. But, given the outstanding success of this “linear” approach, why should we change? The answer is that the water resources needed by this approach are increasingly unavailable due to the factors 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 1,800 years). The population increased from about 1 billion to about 1.65 billion during the 19th century, and from 1.65 billion to about 2.5 billion during the first half of the 20th century. In the second half of the 20th century it more than doubled from about 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 about 9 billion by 2050. It is further estimated that a population plateau of about 10 billion will be reached and then sustained through the second half of the 21st century. These are the median projections. Low end projects (which seem unlikely given current trends) suggest a peak of a bit less than 8 billion in the first half of the 21st century, declining in the second half of the 21st century. High end projections suggest continuing population growth throughout the 21st century. Importantly, avoidance of the high end projection (which would be catastrophic for humankind) requires improvement in the standard of living and educational level for humans living in the developing world, leading to reduced birthrates that will moderate population growth. When it is recognized that only about 1 billion of the planet’s current 6 billion people live in developed countries (which consume a disproportionate fraction of resources), it is clear that resource consumption would have to increase to a much greater extent than population under this scenario if current resource consumption patterns continue. Said another way, if the human population is currently consuming the natural resources of one planet earth, this future scenario would require the resources of three or more planet earths rather than a simple increase in proportion to population growth. This, obviously, is not sustainable. Thus, resource consumption patterns must change (higher standards of living must be accomplished with reduced resource consumption) to mitigate population growth while accommodating a global population increase to only about 10 billion.

Those of us living in the U.S. 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 U.S. population is expected to increase by about 50
percent from its current value of about 300 million to about 450 million over the same 50 year period (from 2000 to 2050). Second, many areas of the US are currently experiencing water stress, and this will increase precipitously over this same period (U.S. Department of Interior, 2005). Finally, we live in a global world, and events occurring outside of the US are increasingly affecting us. Thus, it is not only necessary but also in our best interests to address growing water management needs, both in the U.S. 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.

The population and living standard trends discussed above will not occur uniformly around the world. Due to reduced birthrates and the absence of sufficient immigration it is expected that the population in most developed countries will either remain static or decline. The population of Japan is already beginning to decline, and the population of many Western European countries will either stabilize or decline, depending upon migration patterns. Population growth in the U.S. will be a result of significant immigration, not births by the native population (the birthrate of the native population are similar to those in other developed countries like Japan and most Western European countries). In contrast, significant population growth will occur in the developing countries, leading to increasing population residing there and also feeding immigration to developed countries such as the U.S. and Europe. 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 (NRC, 2003). We have

![Figure 1. Historical (Solid Line) and Projected (Dotted Line) Global Population Projections per the United Nations (2005).](image)
become an urban population, and this will increasingly 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 be thought to occur for a simple reason – the rural population has reached saturation values and may, in fact, decrease as fewer people are needed per unit of production in agriculture. In fact, for the first time in human history more than half the human population is living in urban areas (NRC, 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 under-developed countries.

Table 1. Development of Cities Through the Late 20th and Early 21st Century (NRC, 2003).

<table>
<thead>
<tr>
<th>Item</th>
<th>Number of Cities in Each Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cities with Population of 1 Million or More</td>
<td></td>
</tr>
<tr>
<td>High Income Countries</td>
<td>43</td>
</tr>
<tr>
<td>Middle and Low Income Countries</td>
<td>40</td>
</tr>
<tr>
<td>Cities with Population of 5 Million or More</td>
<td></td>
</tr>
<tr>
<td>High Income Countries</td>
<td>5</td>
</tr>
<tr>
<td>Middle and Low Income Countries</td>
<td>3</td>
</tr>
</tbody>
</table>

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 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 improved nutrient management. Access to sustainable water and sanitation for all must also be achieved to meet the established Millennium Development Goals. Since the existing and future situation is not the same in all locations, the response to achieve these goals will also not be the same. To understand some of these differences it is useful to consider four country types which differ in terms of population growth and changes in standard of living (all are affected by increased urbanization). They are: (1) developed countries with constant or declining population, (2) developed countries with growing population, (3) developing countries (growing population) where living standards will increase, and (4) under-developed countries (growing population but little change in standard of living). Japan and many European countries
represent the first type, while the US 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 is useful to also discuss water management in rural settings. Rural needs have often dominated concerns in developing and under-developed countries because of the historical dominance of rural populations and because in most countries (including the US) 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. Urban areas are generally served by traditional centralized water and wastewater management systems, which are providing adequate service. Rural areas generally receive water supply from ground water sources and wastewater is managed by soil-based systems, which are likewise providing adequate service. The principal issue is the sustainability of these approaches, both the ability to financially and physically sustain the required infrastructure and the associated environmental impacts. Significant concern exists by some with 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 U.S., Australia, and Singapore, growing water needs must be met even though sufficient water supplies do not exist based on current approaches and/or existing supplies are being adversely impacted by global climate change. Water utilities are increasingly using poorer quality compromised water supplies and adopting non-traditional water supply options such as water reclamation and reuse and desalination. Concern exists in some quarters about the financial sustainability of the centralized systems typically used. Interest in decentralized systems is also developing in suburban locations, especially to reduce initial and long-term costs but also to encourage water reclamation and reuse.

The situations in developing and under-developed countries are generally similar. The urban poor often lack access to safe water, and an even larger proportion lack access to appropriate sanitation. Many rural residents also lack access to safe water and appropriate sanitation, while others use traditional water supply and sanitation methods which depend upon pristine water sources which are increasingly unavailable. The principal difference between developing and under-developed countries is that water supply and sanitation are being extended in developing countries at a much greater rate than in under-developed countries. Centralized systems are generally 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 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 about 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 “triple bottom line” as illustrated in Table 3.

**Table 3. Triple Bottom Line Urban Water and Resource Management Sustainability Goals**

<table>
<thead>
<tr>
<th>Sustainability Area</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>• Financially stable utilities with the ability to maintain their infrastructure.</td>
</tr>
</tbody>
</table>
| Environmental       | • Locally sustainable water supply (recharge exceeds net withdrawal).  
                       | • Energy neutral (or positive if possible) with minimal chemical consumption.  
                       | • Responsible nutrient management that minimizes dispersal to the aquatic environment. |
| Social              | • Provide access to clean water and appropriate sanitation for all |

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

**TOOLKIT TO ACHIEVE GREATER SUSTAINABILITY**

Now that we know what must be achieved, the question is how. Fortunately approaches are evolving which 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, (6) source separation. These approaches can be deployed in either a centralized or decentralized fashion. Some of these approaches are well established and well known, while others are more recently introduced and are still evolving. Table 4 summarizes the six approaches.

**Stormwater Management, Water Conservation, and Water Reclamation and Reuse**

Stormwater management and rainwater harvesting represent a diverse set of technologies generally intended to capture stormwater runoff and either treat it for introduction into 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 are generally distributed throughout the urban area and, consequently, are also 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* (Kennedy, *et al.*, 2008; Hyland and Zuravnsky, 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.

![Figure 2. Water Supply Provided by Capture of Local Rainfall as a Function of Population Density.](image)

Water conservation is also a well-established practice and involves a combination of technologies and practices. While behavior changes are certainly encouraged and welcome, the emphasis here is on the use of technologies that result in reduced water use. A wide variety of approaches are available and are being increasingly applied, as evidenced by the recent May, 2008 issue of the *Journal of the American Water Works Association* (Smith, 2008; Pape, 2008; Maddaus, et al., 2008; Hoffman, 2008; Mayer, et al., 2008; Chesnutt, 2008). Anecdotal evidence also suggests reduced domestic water use and the corresponding increase in wastewater strength (since 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 due to 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 reclamation and reuse is an established practice which can dramatically reduce net withdrawal from the environment. Municipal water reclamation and reuse is widely practiced 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: (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 which is capable of previously unknown performance levels, especially membrane technology (DiGiano, et al., 2004). Increasingly stringent discharge standards are also enabling reclamation and reuse as the incremental cost for water reclamation is reduced compared to treatment and discharge options. While municipal water reclamation and reuse for agricultural, industrial, thermal energy, and urban irrigation uses certainly reduce net water consumption, domestic non-potable and potable water reclamation and reuse can provide dramatic reductions in net domestic water reuse 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.

**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 impacts 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 U.S. electrical energy use for urban water treatment, distribution, and wastewater management which is estimated to be 17.5 W/person (Carns, 2007). Compare this to average per capita total U.S. electrical energy consumption of 1,450 W/person (based on total U.S. energy consumption in 2006 of 3,817 Billion kW-hr/yr (U.S. DOE EIA, 2008) and a total population of 300,000,000). Water is often reported to consume about 2 percent of total U.S. 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. Further segregation of this 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 off-set by reduced energy requirements for water supply, treatment, and distribution, potentially offering a net reduction in energy use. For example, it is estimated that approximately 7 percent of total energy use in the State of California is simply to transport water from Northern to Southern California – an energy use which can be significantly reduced through water reclamation and reuse. Systematic analysis of urban water management systems, including water supply, water and wastewater treatment, and conveyance, can result in water supply approaches which inherently require less energy.
The energy present in the wastewater stream, which consists of heat energy and the energy value of organic matter and nitrogen present due to pollutant discharges, can also serve as energy sources. Heat energy may be thought to be present at least partially due to the heat added to the wastewater through use. Using a value of 4,200 J/(L °C) (70 (W · min)/(L °C) for the sensible heat of (waste)water, the heat energy available (for either heating or cooling) may be related to per-capita wastewater production as illustrated in Figure 4. The energy value for organic matter is most easily calculated based on the methane equivalent of the oxygen demand satisfied of 0.35 m³/kg COD equivalent. Using the energy equivalent for methane of 35,800 kJ/m³, and recognizing that 1 J equals 1 (W · sec), 0.145 (W · day) can be produced for every g of oxygen demand converted into energy. Using this factor and various pollutant conversion scenarios, the potential energy supplies listed in Table 5 can be computed. These values represent maximums which are not practically achievable. For example, only approximately 30 to 40 percent of the energy present in biogas is converted into electrical energy in combined heat and power (CHP) applications, and the capture and use of heat energy will increase the overall efficiency to over just 50 percent. To illustrate the potential, however, consider treatment of wastewater in an anaerobic system with a treatment efficiency of 80 %, yields biogas with an energy content of $17.4 \times 0.8$ or 13.9 W/person. If this biogas is captured and converted to electrical energy using a system achieving an efficiency of 35 percent, 4.9 W/person of electrical energy could be produced and over 7 W/person of useful energy would be produced if heat energy is also captured.

Table 6 summarizes technologies that can potentially utilize 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.
Three types of technologies are generally available: (1) anaerobic biological which convert 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 either 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 significant loss in the treated effluent for dilute...
feed streams. This loss is environmentally significant since the global warming potential (GWP) 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 pre-treatment to hydrolyze particulate organic matter (particularly biological cells) prior to 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 either present in the influent wastewater or produced as a result of wastewater treatment. Their efficiency is constrained by the removal of water prior to 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 both the biodegradable organic matter and nitrogen. Constraints include the hydrolysis of particulate matter (which is often limited in biofilm systems), and the efficiency of conversion of liberated electrons to useful energy (which is often on the order of 20% with current devices; Logan, et al., 2006).

**Nutrient Recovery**

Wastewater management systems are critical 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 agricultural 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 di-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, since nitrogen is removed from the atmosphere to produce commercial fertilizer, 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.

The situation with phosphorus is different. Since phosphorus is not returned to the atmosphere, the discharge of phosphorus to the aquatic environment results in net dispersion into the environment. It is surprising, but direct agricultural recycling through biosolids application is relatively ineffective given current practices. The current practice is to apply biosolids at agronomic rates based on nitrogen, not phosphorus, content. This was appropriate when phosphorus removal (either 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 effectively recycle this nutrient.

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; Wood, et al., 1999). In general, phosphate can be recovered as either calcium phosphate (Ca$_3$(PO$_4$)$_2$) or struvite (MgNH$_4$PO$_4$). Improvements continue to be made in the approaches and technologies used. While the economics are currently favorable only in certain circumstances (high biosolids disposal costs) due to 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 about 3 g of total phosphate as P/(person · day).

**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 (direct consumption, cooking) from non-potable (toilet flushing, laundry) water within residential and commercial establishments is also 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 very 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 will be discussed below. Table 7 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, the organic matter content of kitchen wastes and feces, and the relatively high proportion of nutrients contained in urine.

<table>
<thead>
<tr>
<th>Source</th>
<th>BOD$_5$ (g/(person · day))</th>
<th>Total Nitrogen (g-N/(person · day))</th>
<th>Total Phosphorus (g-P/(person · day))</th>
<th>Potassium (g-P/(person · day))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilet Waste</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>20</td>
<td>1.1</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Urine</td>
<td>5</td>
<td>11.0</td>
<td>1.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Kitchen</td>
<td>30</td>
<td>0.8</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Bath/Laundry</td>
<td>5</td>
<td>1.1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>60</td>
<td>14.0</td>
<td>2.6</td>
<td>4.4</td>
</tr>
</tbody>
</table>

SYSTEM CONFIGURATIONS

Centralized, Decentralized, and Hybrid Configurations

The toolkit elements described above 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 a 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 for treatment and disposal or reuse. In contrast, in distributed systems multiple potable and wastewater treatment facilities are provided throughout the service area. A hybrid configuration consists of centralized and decentralized components. As illustrated in Table 8, various toolkit elements are best deployed in either centralized or decentralized/hybrid configurations.

Stormwater management and rainwater harvesting are inherently applicable to decentralized and hybrid configurations. Rainwater is collected for use and/or reintroduced into the local environment. 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 systems can be used to meet potable and non-potable uses and can be deployed in either 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 in-direct potable reuse it is introduced into a water supply source such as a water supply reservoir or groundwater aquifer, whereas for direct potable reuse it is introduced directly into the water distribution system. Indirect potable reuse systems have generally gained the greatest favor as they provide increased public health protection due to 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

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customer. This approach requires a high level of treatment, but only one water distribution system (for potable water) is needed.

### Table 8. Application of Toolkit Elements at Centralized and Decentralized Scales.

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<thead>
<tr>
<th>Toolkit Element</th>
<th>Centralized Systems</th>
<th>Decentralized/Hybrid Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stormwater Management and Rainwater Harvesting</td>
<td>-</td>
<td>Permeable pavements, green roofs, rain gardens, etc.</td>
</tr>
<tr>
<td>Water Conservation</td>
<td>New Technologies and Behavior Changes</td>
<td></td>
</tr>
<tr>
<td>Water Reclamation and Reuse</td>
<td>Treatment for Potable Use and Reuse (Direct and In-Direct)</td>
<td>Treatment for Potable Use and Non-Potable Reuse</td>
</tr>
<tr>
<td>Energy Management</td>
<td>Anaerobic Digestion, Combustion, Microbial Fuel Cells</td>
<td>Capture Heat Energy, Microbial Fuel Cells</td>
</tr>
<tr>
<td>Nutrient Recovery</td>
<td>Land Application of Biosolids, Struvite Recovery</td>
<td>-</td>
</tr>
<tr>
<td>Source Separation</td>
<td>Treatment of Kitchen, Black, and Yellow Wastewater</td>
<td>Supply Potable and Non-Potable; Treatment of Kitchen, Black, and Yellow Wastewater</td>
</tr>
</tbody>
</table>

In a decentralized system, water reclamation facilities are strategically located 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 both the capital and operation and maintenance (O&M) cost for several smaller wastewater treatment plants was found to be significantly higher than that for a single, larger wastewater treatment plant. Concerns have also 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 (DiGiano, *et al.*, 2004; Daigger, 2003). More recently this concept has been extended to even smaller scale, with systems (especially membrane bioreactors, MBRs) used to reclaim water for non-potable uses in residential and commercial buildings (Daigger, *et al.*, 2005).
Energy management and nutrient recovery technologies are often best implemented on a more centralized scale due to economies of scale. For example, a relatively small CHP system would have an electrical output of 100 kW. Previous calculations indicated 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. Likewise, aggregation of the nutrients from many individuals may be necessary to make the operation of a nutrient recovery facility practical. The development of microbial fuel cells is still in its infancy and, consequently, their optimum size range is not yet defined. In contrast, 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. Source separation is inherently applied 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 into 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 can also 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 Sewerage Authority (UOSA) represents a long-standing (30 year) example where a 205,000 m³/day (54 mgd) in-direct 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: (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 wastewater treatment plants. A portion of the treated effluent is discharged to the ocean, but an increasing proportion is reclaimed as NEWater and either distributed to industry or reintroduced into the potable water supply (in-direct potable reuse). Many industries value the higher quality of NEWater because of its lower total dissolved solids (TDS) content due to the incorporation of reverse osmosis (RO) treatment. An aggressive public communication and water conservation program is helping to reduce water use. Stormwater and local water management are also being
incorporated into 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 Clean. Although Singapore is located in a tropical setting with significant rainfall, the high population density for this island nation creates severe water shortages if only local water supplies were to be relied upon using traditional approaches. Imported water will be used as available, but 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 their future water supply, water reclamation and reuse is much more important in terms of the total volume provided due to the much lower cost and environmental burden associated with NEWater production due to much lower TDS concentrations. This approach provides a flexible portfolio of water supply options as the population increases from the current value of about 4.5 million to a projected future population of 7 million.

Others are incorporating decentralized elements into 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 is also 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. Potable supply is provided by a potable water aquifer, which could also be recharged by either 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 can also be removed by RO and discharged to a saline aquifer if necessary. 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 since 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.
Figure 5. Example Decentralized Urban Water Management System (From Daigger, 2008).

Source separation is a particularly interesting option to facilitate decentralized water management and centralized organic matter management 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 due to 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. 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 would also 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 due to reduced fouling. Perhaps even more important would be reductions in energy requirements for water heating due to reduced water consumption. Reduced pumping for water distribution will also 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 · day), energy neutrality for urban water management can be achieved, along 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 can then 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 is also made more achievable by these approaches. But, 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 been. 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 are too often managed by multiple utilities within urban areas (different political jurisdictions, stormwater vs. water vs. wastewater utilities). A further factor is the practice by the water management profession of “stove piping” 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 is often 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 impacts of climate change on water supply issues, as illustrated by the recent drought in the Southeastern U.S. Likewise, the emergence of greenhouse gas (GHG) 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!


<table>
<thead>
<tr>
<th>Guiding Principles</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Protect and subsequently use locally available water resources whenever possible.</td>
<td>1. Maintain water balance for both typical and extreme (wet and dry) conditions.</td>
</tr>
<tr>
<td>Generally means infiltration of high frequency, low-intensity storms and allowing high-intensity storms to create run-off.</td>
<td>3. Maintain nutrient balance.</td>
</tr>
<tr>
<td>3. Public health is protected by incorporating multiple barriers, especially considering pathogens and trace contaminants.</td>
<td>4. Manage residuals, both over short and long time scales.</td>
</tr>
<tr>
<td>4. Consider total resource consumption and potential for resource recovery when formulating systems.</td>
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</tbody>
</table>

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 impacts on the entire water supply and wastewater management system, including water resources. Moreover, since their implementation will either 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 incremental costs. For example, the economics of water reclamation and reuse options should not be evaluated based on the average cost of water supplied to the urban area, but on the most expensive water supply option as it is
this option which will be avoided. A clear articulation of the incremental costs for any subject
system will also allow rapid screening of the economics of various options.

Institutional barriers must also 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 our 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 is also perceived that the existing urban infrastructure represents a barrier to implementation of
these potentially higher performing systems. Since our 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 are
also 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 must
also be funded which will generally 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 which 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
successfully addressed, 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, financial) to do so, and the need to serve growing populations. In so doing we
will also contribute to progress in the developing and under-developed countries by creating
more efficient and effective models that can be implemented there to meet the existing
significant and growing need. One may also suspect that necessity will drive innovation,
especially in developing countries. Our failure to seize the opportunity before us will negatively
affect us both 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 upon 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 that is both 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) to accommodate increasing water scarcity caused 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 are also needed to increase the financial stability or urban water management utilities. Fortunately new approaches are evolving which offer the promise to deliver much higher performance, including: (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) have already 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 which are the most sustainable. Economic evaluations need to consider systematic impacts 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 re-development occurs. The greatest institutional barrier to implementation of improved systems is probably the stove piping of the urban water management profession, a situation which can be addressed. Developed countries with growing populations like the U.S. 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.

ACKNOWLEDGMENTS

This paper 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 I have been participating in began in 2001 when I was the American Academy of Environmental
Engineers (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 National Academy of Engineering (NAE) initiative on urban sustainability, presentation of the American Society of Civil Engineers (ASCE) Simon W. Freese Lecture in 2006, and keynote/plenary lectures at the International Water Association (IWA) 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, on this manuscript were particularly helpful and are gratefully acknowledged. Thanks to 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 which remain true to their core principles but which continue to adapt their practices to practical realities survive (are sustainable), but those which 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 twenty greatest engineering achievements of the 20th century (Constable and Sommerville, 2003). Having achieved this outstanding achievement in the 20th century, the question is how will our profession adapt to the altered circumstances of the 21st century? Following Jared 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. I 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.

REFERENCES


Smith, S. W., (2008) From the Farm to the City: Using Agricultural Supplies to Irrigate Urban Landscapes, *Jour. AWWA*, 100(5), 96-100.


<table>
<thead>
<tr>
<th>Country Type</th>
<th>Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed, Constant or Declining Population</td>
<td>Generally traditional centralized water supply and wastewater management systems which provide adequate service but are increasingly judged to not be sustainable. Significant improvements needed to reduce net water consumption, reduce energy, and recover nutrients.</td>
<td>Water supply generally by ground water and wastewater management by soil-based systems. Enhanced community and on-site systems adopted in some instances. No changes needed.</td>
</tr>
<tr>
<td>Developed, Growing Population</td>
<td>Generally traditional centralized water supply and wastewater management systems which provide adequate service but are increasingly judged to not be sustainable. Significant water supply problems in areas with growing population which are driving increased use of novel water supply approaches, such as water reclamation and reuse.</td>
<td>Water supply generally by ground water 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.</td>
</tr>
<tr>
<td>Developing</td>
<td>Water provided by public water supply not generally considered to meet potable water standards and often not available in poorer sections. Wastewater collection often present in more affluent areas but absent in poorer sections. Significant efforts to install centralized systems in more rapidly developing urban locations.</td>
<td>Water supply and waste management often by traditional means. Significant number of residents lack access to safe water and appropriate sanitation.</td>
</tr>
<tr>
<td>Under-Developed</td>
<td>Water provided by public water supply not generally considered to meet potable water standards and often not available in poorer sections. Wastewater collection often present in more affluent areas but absent in poorer sections. Little progress being made to improve water supply and sanitation.</td>
<td>Water supply and waste management often by traditional means. Significant number of residents lack access to safe water and appropriate sanitation.</td>
</tr>
<tr>
<td>Option</td>
<td>Feedstock</td>
<td>Constraints</td>
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<td>-------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
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<tr>
<td>Anaerobic Treatment</td>
<td></td>
<td></td>
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<tr>
<td>Direct</td>
<td>Biodegradable organic matter</td>
<td>• Organic matter conversion efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Loss of methane in treated effluent due to solubility</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Hydrolysis of particulate organic matter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Conversion of biogas to energy</td>
</tr>
<tr>
<td>Sludge</td>
<td>Settleable biodegradable organic matter in wastewater plus biodegradable</td>
<td>• Organic matter conversion efficiency</td>
</tr>
<tr>
<td></td>
<td>matter in downstream biological treatment</td>
<td>• Hydrolysis of particulate organic matter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Conversion of biogas to energy</td>
</tr>
<tr>
<td>Sludge (staged, pre-treated)</td>
<td>Settleable biodegradable organic matter in wastewater plus biomass</td>
<td>• Organic matter conversion efficiency</td>
</tr>
<tr>
<td></td>
<td>produced in downstream biological treatment</td>
<td>• Conversion of biogas to energy</td>
</tr>
<tr>
<td>Thermal</td>
<td>Particulate organic matter in wastewater plus biomass produced in</td>
<td>• Proportion of water which must be evaporated compared to organic matter</td>
</tr>
<tr>
<td></td>
<td>downstream biological treatment</td>
<td>which can be combusted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Efficiency of use of thermal energy</td>
</tr>
<tr>
<td>Combined Thermal/Biological</td>
<td>Particulate organic matter in wastewater plus biomass produced in</td>
<td>• Constraints of thermal and biological systems applied</td>
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<tr>
<td></td>
<td>downstream biological treatment</td>
<td></td>
</tr>
<tr>
<td>Microbial Fuel Cells</td>
<td>Biodegradable organic matter (current application and nitrogen (future</td>
<td>• Hydrolysis of particulate organic matter and nitrogen</td>
</tr>
<tr>
<td></td>
<td>potential)</td>
<td>• Efficiency of conversion of liberated electrons to useful energy</td>
</tr>
</tbody>
</table>
### Table 4. Toolkit to Achieve Increase Urban Water and Waste Management Sustainability.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Example Technologies</th>
<th>Contribution to Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stormwater Management and Rainwater Harvesting</td>
<td>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 either infiltrate a portion into the groundwater or allow evapo-transpiration by vegetation to later return it to the atmosphere (Strecker, <em>et al.</em>, 2005)</td>
<td>Permeable pavements, green roofs, rain gardens, bioretention basins. Also known as Low Impact Development (LID).</td>
<td>Local potable and non-potable water supply, pollutant removal to protect water resources.</td>
</tr>
<tr>
<td>Water Conservation</td>
<td>The application of technologies which provide expected service with reduced water use, potentially coupled with behavior changes</td>
<td>Low flow shower heads, toilets, washing machines; drip irrigation.</td>
<td>Significant reduction in water use.</td>
</tr>
<tr>
<td>Water Reclamation and Reuse</td>
<td>The treatment of wastewater (reclamation) for subsequent use as a water supply (reuse).</td>
<td>Wide variety depending on wastewater and reclaimed water quality requirements.</td>
<td>Agricultural, industrial, irrigation, domestic (potable and non-potable) water supply.</td>
</tr>
<tr>
<td>Energy Management</td>
<td>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. The application of energy efficient approaches.</td>
<td>Anaerobic treatment, thermal combustion with energy recovery, microbial fuel cells.</td>
<td>Reduced energy required for treatment and/or energy recovery.</td>
</tr>
<tr>
<td>Nutrient Recovery</td>
<td>The production of products from wastewater which can be used as fertilizers due to their nutrient value.</td>
<td>Land application of biosolids, struvite precipitation</td>
<td>Reuse of nutrients reduces withdrawal from the environment.</td>
</tr>
<tr>
<td>Source Separation</td>
<td>Separate collection of various human waste sources reflecting their different characteristics and potential uses.</td>
<td>Grey water, Black water, Yellow water.</td>
<td>Enables approaches which use less energy and/or improved nutrient recovery.</td>
</tr>
</tbody>
</table>