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TECHNOLOGIES FOR CLEAN WATER

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Integrated closed-loop systems for recycling water and waste material can meet consumer demands and satisfy environmental imperatives.

New Approaches and Technologies for Wastewater Management

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In the past decade, practical applications of a variety of new wastewater-treatment technologies, such as membrane filtration systems and advanced oxidation, have led to new ways of managing urban water systems and water resources (Daigger, 2003). These new treatment regimes, especially the integration of urban-water and waste-management systems, promise to dramatically improve the sustainability of our water resources.

These new systems are creating new needs, which are driving further technology development. In this paper, I discuss the circumstances that have necessitated change in urban water and resource management; describe some of the changes that are already being implemented; and describe technological advances that are under development.

The Need for Change

The major driver of change is, quite simply, population growth coupled with a rising global standard of living, a combination that has resulted in resource consumption (including water use) that exceeds the current resources of planet Earth (Daigger, 2007b, 2008a; Wallace, 2005). Let's say the current population of slightly more than 6 billion consumes the resources of one planet Earth. By about 2050, when the population is expected to reach about 9 billion, and if standards of living continue to rise, the amount consumed will be the resources of about three planet Earths. Obviously, this scenario is not sustainable.

When the population of Earth was much smaller (e.g., fewer than 2 billion) and when per capita use of resources was much smaller, our traditional "take, make, waste" pattern of resource consumption was sustainable. Now, however, we need to recycle and reuse all types of resources (including water), and we must increase our use of renewable resources.

Water Stress

In contrast to many other natural resources, water is inherently renewable. Mother Nature has been recycling water since the origin of life on the planet. When the rate of net abstraction and use of water prior to its being returned to the environment exceeds the natural rate of recycling, water stress develops. Water-management practices can add to water stress by reducing the amount of water available, for example by returning water to the environment in a polluted state or by altering land configurations in ways that adversely affect natural water-restoration processes, such as those provided by wetlands.

Water stress currently affects only a modest fraction of the human population, but it is expected to affect 45 percent of the population by 2025 (Daigger, 2007b; WRI, 1996). This situation will be further exacerbated by global climate change, which is altering water-supply and storage patterns in ways that make existing water-management infrastructure less effective.

Recycling technologies can significantly reduce net water abstraction from the environment, but many of those technologies require an increase in the consumption of other resources, especially energy. In our resource-constrained world, increasing the consumption of any resource, even for necessary functions such as water management, must be carefully considered.

A further aspect of water stress caused by urban water-management systems is the increase in the amount of nutrients, especially phosphorus, in the aquatic environment (Steen, 1998; Wilsenach et al., 2003). Mined as phosphate rock, phosphorus is used to manufacture fertilizer, which in turn is used to grow crops that are subsequently consumed by humans. Phosphorus (and other nutrients) then pass through us as we metabolize food and end up in the wastewater stream. When these effluents are discharged to the aquatic environment, the excess nutrients can cause eutrophication. At the current rate of consumption, the supply of phosphate, an essential nutrient with no known replacement, is expected to be exhausted in about 100 years. Thus, there are at least two urgent reasons for us to recover phosphate from the wastewater stream.

Two other factors must be taken into consideration. First, although water service is uniformly provided in the developed world, approximately 1 billion of the people on Earth do not have access to safe drinking water, and more than 2.5 billion do not have access to adequate sanitation. Clearly, we need more efficient urban water management to meet global needs. Second, water and wastewater utilities around the world are hard pressed to find sufficient funding to maintain, let alone extend, their infrastructure to meet growing needs.

Definition of Sustainability

The need for new approaches to urban water and resource management is being driven by the need for sustainability, defined as: (1) access for all to clean water and appropriate sanitation; (2) greater use of local water resources; (3) energy neutrality; (4) more responsible nutrient management; and (5) financially stable utilities.

Taken together, the requirements for sustainable urban-water and resource-management systems are consistent with the "triple bottom line" definition of sustainability (Table 1), which includes social, environmental,

TABLE 1 Triple Bottom Line Urban-Water and Resource-Management Sustainability Goals

Sustainability Area	Goal
Economy	• Financially stable utilities with enough resources to maintain their infrastructure.
Environment	• Locally sustainable water supply (recharge exceeds net withdrawal). • Energy-neutral system (or positive if possible), with minimal chemical consumption. • Responsible nutrient management that minimizes dispersal to the aquatic environment.
Society	• Access to clean water and appropriate sanitation for all.

and economic goals (Daigger and Crawford, 2005). The economic goal is for utilities to provide sufficient value that their users are willing to financially support maintenance (and expansion) of necessary infrastructure. Environmental goals include meeting water needs from locally available water supplies while maintaining energy neutrality, minimal chemical consumption, and responsible nutrient management. The overall social goal is to provide uniform access to clean water and appropriate sanitation for all.

The challenge is to develop and implement approaches to urban water and resource management, and the supporting technologies, to meet all of these goals. If we can do that, we will have sustainable systems today and in the future.

Achieving Sustainability Goals

Meeting the environmental goals outlined above will require that we evolve from the current linear approach to water and resource management to closed-loop systems, with a combination of decentralized and centralized elements, for recycling both water and waste material (Daigger, 2007a, 2008a,b; Daigger and Crawford, 2007). Because of their superior environmental performance, closed-loop systems have the potential to satisfy the social and economic goals of sustainability, as well as the environmental goals.

Figure 1 illustrates one closed-loop system for urban water management. Note that the water supply, both domestic and commercial, is segregated into water for potable uses, such as direct consumption and bathing, and water for non-potable uses, such as toilet flushing, laundry, irrigation, and industrial uses. Overall, the amount of potable water consumed is actually quite small. Thus the amount of water from the environment necessary for this purpose is much smaller than the amount of potable water currently provided. In fact, the demand for potable water can be met either from local water supplies or by importing modest quantities of potable water. By separating potable and non-potable water, the net removal of water from the environment for potable uses can be dramatically reduced.

The bulk of the domestic and commercial water supply is non-potable water, which can be supplied from a variety of local sources, including recycled water and captured rainwater. As Figure 1 shows, the storage of non-potable water is a critical component of the system. Non-potable water can be stored either in an aquifer beneath the urban area (as shown in Figure 1) or in a surface storage facility.

The repeated recycling of water may result in the buildup of dissolved solids, including salts, which must be managed to maintain the quality of the water for its intended uses. Reverse osmosis (RO) and other processes can be used to remove the salt, which can then be discharged to a saline-water aquifer (Figure 1) or managed in another way.

Many have asked why water needs cannot be met by increasing the desalination of seawater. Although this is technologically feasible, desalination does not meet the environmental criteria for sustainability because of its significant energy requirements. Even though technological advances continue to reduce these energy requirements, they will always be higher than for treating fresh wastewater, because the solids content of wastewater (1,000 mg/L) is much smaller than of seawater (35,000 mg/L).

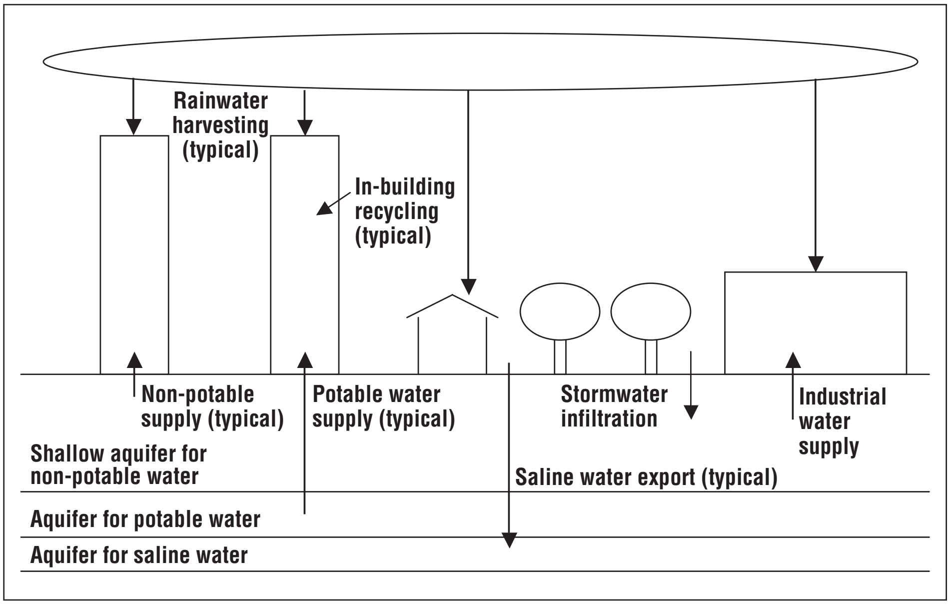

FIGURE 1 Diagram of a decentralized urban water-management system. Source: Daigger, 2008a.

TABLE 2 Tools in Centralized and Decentralized Systems

Tools	Centralized Systems	Decentralized Systems
Storm water management and rainwater harvesting		Permeable pavements, green roofs, rain gardens, etc.
Water conservation	New technologies and behavioral changes	
Water reclamation and reuse	Treatment for potable uses and reuse (direct and indirect)	Treatment for potable uses and non-potable reuse
Energy management	Anaerobic digestion, combustion, microbial fuel cells	Capture of 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 water; treatment of kitchen, black, and yellow wastewater

Technologies for Sustainable Systems

Fortunately tools are available for: (1) more efficient capture and local use of storm water to help conserve local water resources; (2) improved water conservation for reducing water consumption without compromising standards of living; (3) the reclamation and reuse of wastewater; (4) the management and extraction of energy from the wastewater stream; (5) the recovery of nutrients; and (6) the separation of specific wastewater sources. Many technologies are available to facilitate the implementation of systems such as the one shown in Figure 1 and for improving decentralized and centralized water and resource management (Table 2). The goal is to conserve local water resources for meeting a variety of local needs.

Technologies are available for managing storm water, which can be captured and either used directly or treated by natural means and infiltrated into the groundwater for subsequent use (Strecker et al., 2005). These technologies include permeable pavements, green roofs, and rain gardens. In the past decade, as the characterization and understanding of these systems has improved, storm water capture and treatment have become much more reliable and predictable.

Water- and wastewater-treatment technologies are crucial components of urban water systems. Membrane technologies for removing particulate matter (micro- and ultra-filtration) and dissolved substances (nanofiltration and RO) are increasingly being used. When particle-removal membranes are coupled with biological systems, they can create membrane bioreactor (MBR) processes, which are fast becoming an essential water-reclamation process (Daigger et al., 2005; DiGiano et al., 2004). Advanced oxidation processes include combinations of ozone, ultraviolet (UV) light, and hydrogen peroxide to create the highly reactive hydroxyl radical (OH). In addition, activated carbon is still widely used for water reclamation.

Tools That Address Environmental Goals

The remaining tools in the technology tool kit do not necessarily reduce the overall abstraction of water but do contribute significantly to meeting environmental goals, such as energy neutrality and reduced nutrient dispersion. For example, as Figure 2 shows, laundry and bath water (typically referred to as gray water), which contain very few pollutants, constitute the largest component of urban wastewater (Henze and Ledin, 2001; Tchobanoglous, 1981). Because of its low-pollutant content, gray water requires only a modest degree of treatment to become reusable non-potable water. Thus recycling this large volume of wastewater requires less energy, and thus consumes fewer resources, than recycling combined potable and non-potable wastewater. In addition, heat can be transferred to or from the treated gray water stream using specially designed heat exchangers and heat pumps, which represents a significant source of energy.

Organic matter in the several components of the wastewater stream represents a principal source of energy, in addition to the heat value of the water itself. As shown in Figure 2, most of the organic matter (quantified as the five-day biochemical oxygen demand, or BOD_5) is contained in toilet and kitchen waste (typically referred to as black water). The wastewater flow associated with these components is quite small, suggesting that the black-water fraction can be used efficiently for energy production. Energy-producing technologies for organic matter in black water include thermal combustion and anaerobic treatment for producing biogas (Grady et al., 1999), which can be used in combined heat and power systems. The microbial fuel cell is an emerging energy-production technology (Logan et al., 2006).

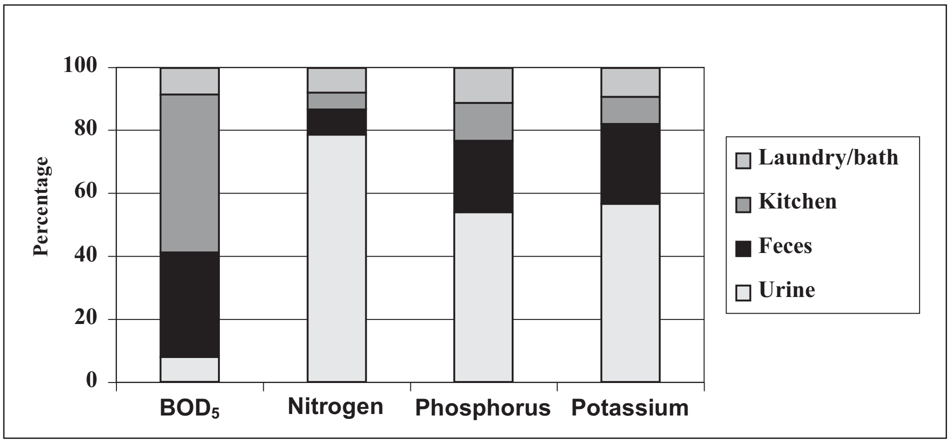

FIGURE 2 Distribution of constituents in domestic wastewater from different sources. Source: Henze and Ledin, 2001.

The majority of nutrients is found in the urine stream (typically referred to as yellow water). When energy management and nutrient recovery are combined with source separation, energy can be efficiently produced and extracted from the wastewater stream, along with nutrient recovery. A variety of technologies are available for nutrient recovery. For example, biosolids containing nitrogen and phosphorus, produced from treatment and nutrient-recovery processes, can be applied directly to agricultural lands as fertilizer. A second approach is to apply phosphate fertilizers, containing either struvite ($MgNH_4PO_4$) or calcium phosphate, produced from the chemical precipitation of phosphorus.

As suggested in Table 2, storm water capture and water-reclamation technologies are most effective at the local (decentralized) level. Water-reclamation technologies result in reduced pumping requirements because the reclaimed water is produced closer to where it is used. By contrast, energy-management and nutrient-recovery technologies are most effective in large-scale centralized systems. Figure 3 shows an integrated system that uses all of these features and indicates the scale at which the various technologies would be applied.

New Technologies

Membrane Filtration Systems

Membrane systems have been critical to the development of advanced water-reclamation systems, and the development of new and improved systems is expected to continue. Immersed micro- and ultra-filtration membranes provide excellent pre-treatment for RO, which can remove a wide range of dissolved constituents. In addition, the development of membrane filtration systems has led to the development of both advanced water-treatment technology and MBRs, which is fast becoming the workhorse of the water-reclamation industry.

With MBRs, biological-solids residence times (SRTs) are increased, making possible more complete biological treatment and the retention of pathogens (including viruses); treatment with MBR produces a highly clarified effluent that can be more easily disinfected. Thus treatment with MBR is ideal for producing nonpotable water. For the reclamation of potable water, MBR must be followed by RO and UV treatment (Tao et al., 2005, 2006).

Nanotechnology

Further dramatic improvements are feasible in the near future (Shannon et al., 2008). Nanotechnology concepts are being investigated for higher performing membranes with fewer fouling characteristics, improved hydraulic conductivity, and more selective rejection/transport characteristics. Advances in RO technology include improved membranes and configurations, more efficient pumping and energy-recovery systems, and the development of process technology, such as membrane distillation (Kim et al., 2008).

Microbial Fuel Cells

With microbial fuel cells, a potential breakthrough technology, electrical energy could be extracted directly from organic matter present in the waste stream by using electron transfer to capture the energy produced by microorganisms for metabolic processes (Logan et al., 2006). First, microorganisms are grown as a biofilm on an electrode; the electron donor is separated from the electron acceptor by a proton exchange membrane, which establishes an electrical current. Electrical energy is then generated through the oxidation of organic matter (BOD_5).

Although this technology is still in the early stages of development and significant advances in process efficiency and economics will be necessary, it has the potential to produce electrical energy directly from organic matter in the waste stream.

Natural Treatment Systems

Our fundamental understanding and characterization of processes in natural treatment systems (NTSs) is also improving, enabling us to take advantage of natural processes to improve water quality (Kadlec and Knight, 1996). In NTSs, a variety of physical, chemical, and biological processes function simultaneously to remove a broad range of contaminants.

For example, NTSs are increasingly being used to capture, retain, and treat storm water, thereby converting this "nuisance" into a valuable source of water. These natural systems have the advantage of being able to remove a wide variety of contaminants, including nutrients, pathogens, and micro-constituents (e.g., pharmaceuticals and endocrine-disrupting chemicals). Long proven effective for treatment of potable water, NTSs are increasingly being used for water reclamation.

Urine-Separating Toilets

As shown in Table 2 and illustrated in Figure 3, the development of urine-separating toilets and technologies for treating urine to produce hygienic fertilizer products is a key to managing nutrients with minimal requirements for outside resources, such as additional energy (Larsen et al., 2001; Maurer et al., 2006). Urine-separating toilets have already been developed and continue to be refined, and research on using them for waste management is ongoing. Struvite precipitation and other processes are already available for producing usable fertilizer products from separated urine, and efforts are ongoing to improve the established approaches.

Monitoring and Control Systems

The complex systems illustrated in Figure 3 will require sophisticated monitoring and control systems. The production and consumption of reclaimed water must be balanced so as not to exceed available storage capacity and to take into account variations in supply from rainwater. Water production must also be managed to maintain the integrity of the overall system and, particularly, the efficiency and effectiveness of the barriers that protect public health, such as the separation of potable and non-potable water. In addition, because energy requirements vary diurnally and seasonally, energy consumption also requires active management. Research on a new generation of sensor and system-control technologies is ongoing (Shannon et al., 2008).

Concluding Thoughts

Even though a survey by *BMJ* (formerly *British Medical Journal*) found that modern water supply and sanitation is the most significant contribution to public health in the past 150 years (BMJ, 2007), and the National Academy of Engineering listed modern water-supply

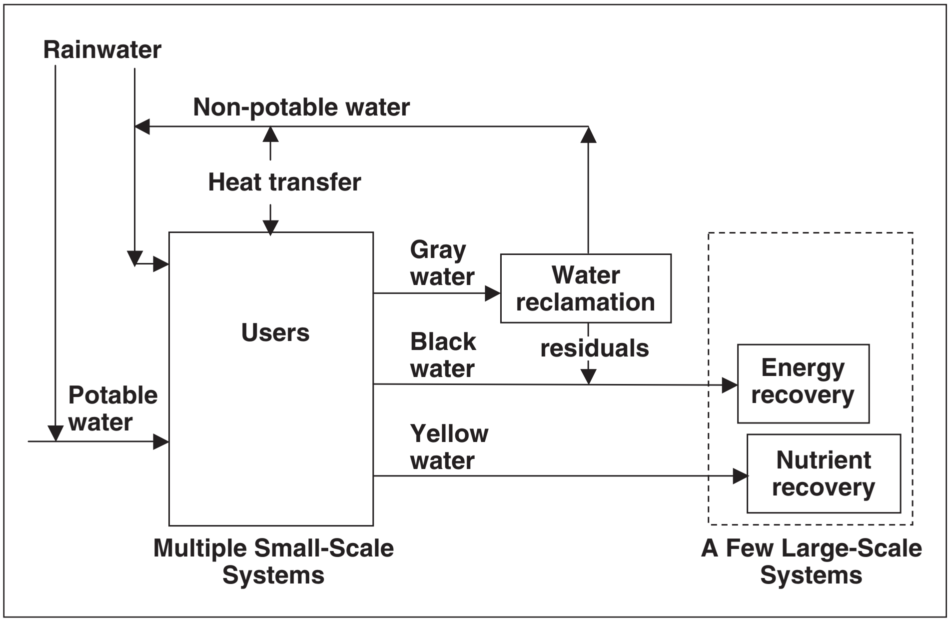

FIGURE 3 Schematic drawing of an integrated urban-water and resource-management system.

and sanitation systems as one of the greatest engineering achievements of the 20th century (Constable and Sommerville, 2003), circumstances have changed, and new approaches to water and sanitation systems are urgently needed. Thus we are faced with many new, interesting, and important challenges.

Fortunately many technologies to meet these challenges already exist, and work is being done on refining them and integrating them into higher performing, more sustainable systems. These are all areas in which engineers excel!

The "companion" challenge will be choosing among available options and developing institutional arrangements for implementing them in the most effective ways (Daigger, 2007a,b; 2008a,b; Daigger and Crawford, 2005). This is where we will need help from other professions.

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