Recovering SUSTAINABLE Water *from* Wastewater

AUDREY D. LEVINE
UNIVERSITY OF SOUTH FLORIDA, TAMPA

TAKASHI ASANO
UNIVERSITY OF CALIFORNIA, DAVIS

Society no longer has the luxury of using water only once.

For water supplies to be sustainable, the rate at which water is withdrawn from water sources needs to be in balance with the rate of renewal or replenishment. At the same time, water quality must also be sustainable or recoverable. In nature, precipitation replenishes surface water supplies and recharges groundwater. However, urbanization, agriculture, dams and reservoirs, and other shifts in land-use patterns are altering the rate, extent, and spatial distribution of freshwater consumption and replenishment. Therefore, water withdrawn for societal needs must also be considered a source in the sustainability equation.

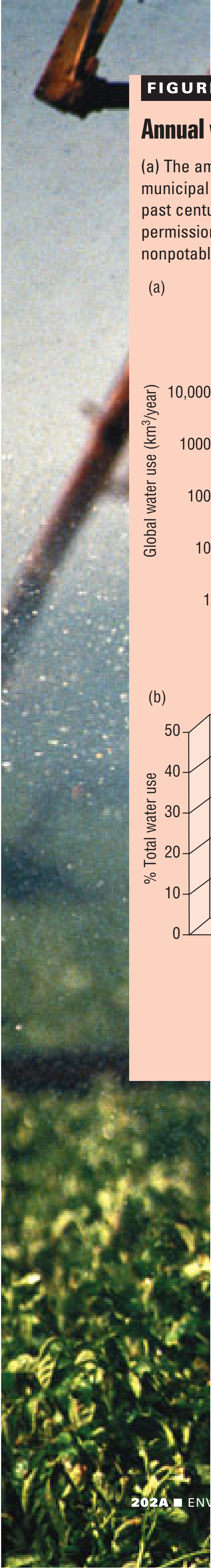
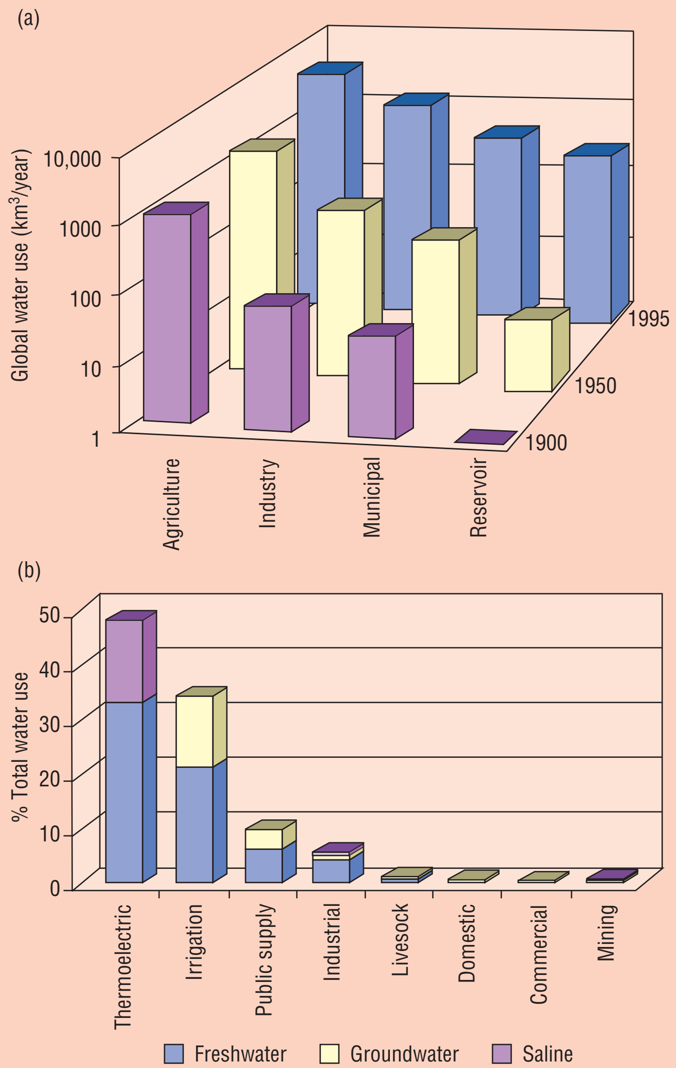


FIGURE 1

Annual water use

(a) The amount of water withdrawn for agriculture, industry, and municipal applications around the world has grown steadily over the past century. Reservoir water use refers to evaporation. (Adapted with permission from Ref. 3.) (b) The amount of water used for potable and nonpotable applications varies. Data from Ref. 25.



Sustainable water resources are particularly important in light of projected increases in global population. The current world population of 6.2 billion is increasing at a rate of about 1.2% per year (*1*), with the highest rates of growth occurring in urban areas. This increasing urbanization has resulted in an uneven distribution of population and water, imposing unprecedented pressures on limited water supplies, which are exacerbated during periods of drought.

On a global scale, about 3800 cubic kilometers of water per year are withdrawn to meet societal needs. The total available volume of renewable freshwater is several times more than is needed to sustain the current world population. However, population centers can access only about 31% of the renewable water because of geographical constraints and seasonal variations (*2*).

Historically, after water was used for societal needs, it was labeled as sewage or wastewater and treated for discharge into receiving water or for land disposal. During most of the 20th century, wastewater treatment emphasized pollution abatement, public health protection, and prevention of environmental degradation through removal of biodegradable material, nutrients, and pathogens. However, over the past few decades, people have recognized the potential for recovering water from wastewater. In fact, in many parts of the world, using water only once is no longer an option. In this article, we summarize how water reuse has emerged as a vital component of sustainable water resources management.

Water usage patterns

Human society requires water for drinking, sanitation, cleaning, production of food and energy, and support of commercial and industrial activities. Figure 1a shows how water is used on a global scale. Currently, irrigation comprises about 65% of all water use; industries use about 20%; and municipalities consume another 10% (*3*). (To complicate matters, it is interesting to note that the volume of water evaporated from surface water impoundments [reservoirs] increased dramatically during the 20th century.)

To gain insight into the major uses of water, it is important to analyze water withdrawals in relationship to the hydrologic cycle. For example, 30–90% of the water that is withdrawn for irrigation is consumed through evaporation, incorporation into crops, and transpiration. The remaining water either percolates to groundwater or is released as drainage or returns unused from the field. In contrast, most water used for municipal purposes is collected as wastewater and treated and has the potential to be reclaimed and reused.

Currently, about one-third of the world's population lives in countries that face moderate to severe water shortages. An estimated 25% of the world's population lacks access to clean drinking water and protection from waterborne disease (*4*). The World Bank projected that, over the next century, the quantity of available water must increase by 25–60% to meet global needs, depending on how efficiently it is used (*4*). Water consumption in cities ranges from 200 to 600 liters per capita per day, depending on the standard of living, water-use efficiency, and integrity of the water transmission system (*3*).

Water in an urban environment has characteristics that distinguish it from other commodities. First, the amount of water that urban populations consume dwarfs the quantity of all other supplies and products. However, unlike other commodities that are consumed or destroyed through use, such as fuel or food, water undergoes only small, though important, modifications before it is discharged as wastewater (*5*; a glossary of terms is on facing page).

Because most wastewater is collected in a conveyance system, urban water can be treated and reused for alternative applications. Thus, reclaimed water yields a resource that could prevent the high costs of importing freshwater and conveying it over a long distance. In addition, a water supply recovered from wastewater is somewhat drought-tolerant because it is linked to water-use patterns of the resident population and is less vulnerable to low water conditions associated with drought-prone surface water sources.

Reclaimed water primer

Over the past two decades, the amount of municipal wastewater recovered for reuse has increased throughout the world. The primary incentives for implementing water reuse are augmentation of water supplies and/or pollution abatement. Water reuse can be categorized as "direct" or "indirect", depending on whether the reclaimed water is used directly or mixed with other sources. On an international scale, direct non-potable water reuse is currently the dominant mode for supplementing public water supplies for irrigation, industrial cooling water, river flow augmentation, and other applications (*6*).

On the other hand, unplanned, indirect potable water reuse, through wastewater effluent disposal to streams, rivers, and groundwater basins, has been an accepted practice around the world for centuries. Communities situated at the end of major waterways have long histories of producing potable water from river water sources that have circulated through multiple cycles of withdrawal, treatment, and discharge. Similarly, riverbeds or percolation ponds may recharge underlying groundwater aquifers with wastewater-dominated water, which, in turn, is withdrawn by down-gradient communities for domestic water supplies. The safeguards for this unplanned indirect potable reuse are often carried out by advanced water treatment technologies.

Planned indirect water reuse involves linking the discharge of treated wastewater with potential downstream water uses. For example in Los Angeles County, Calif., a groundwater recharge program has reclaimed water for indirect potable use since 1962 (*7, 8*), and in northern Virginia, the discharge of highly treated municipal wastewater by the Upper Occoquan Sewage Authority to the upper reaches of the Occoquan Reservoir has been in effect since 1978. Virginia's reservoir serves as the principal drinking water supply source for approximately 1 million local residents (*9*).

Applications for reclaimed water

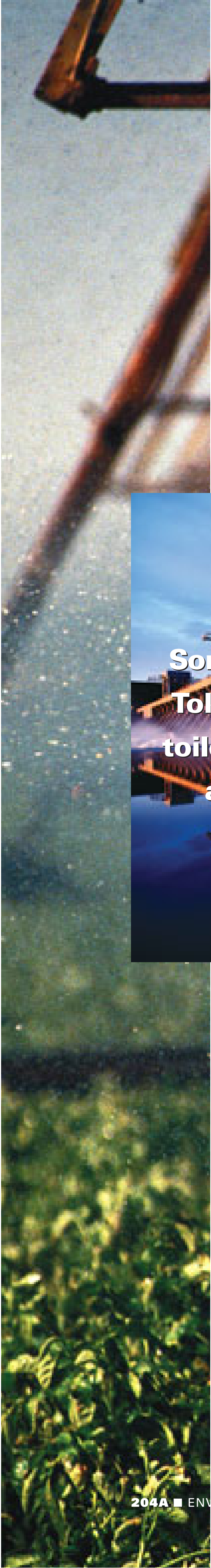
Opportunities for using reclaimed water can be gleaned by reviewing the relative quantities of water needed for individual applications. A comparison of water-use patterns in the United States is shown in Figure 1b. The dominant non-potable uses of freshwater include irrigation, industrial use, surface water replenishment, and groundwater recharge—all of which could be augmented or replaced by reclaimed water with the appropriate level of treatment. The specific distribution of reclaimed water is related to local water usage patterns. For example, suburban areas in Florida tend to use reclaimed water for landscape irrigation, whereas urban areas use it as a source for industrial cooling, such as for waste-to-energy fa-

Terminology used to describe water reuse

Term	Definition
Processing	Application of treatment technology to modify water quality.
Water recycling	Recovery of wastewater from a specific use and redirection of the water back to the original use; typically involves only one use or user. Applied predominantly to industrial applications, such as in the steam–electric, manufacturing, and minerals industries.
Wastewater reclamation	Treatment or processing of wastewater to make it reusable.
Product	End result of treatment.
Reclaimed water	The end product of wastewater reclamation that meets water quality requirements for biodegradable materials, suspended matter, and pathogens.
Recycled water	Reclaimed water that meets appropriate water quality requirements and is reused for a specific purpose.
Water reuse	Beneficial use of treated wastewater.
Direct reuse	The direct use of reclaimed water. Applications include agricultural and landscape irrigation, cooling water and other industrial uses, urban applications, and dual water systems.
Indirect reuse	Mixing, dilution, and dispersion of treated wastewater by discharge into an impoundment, receiving water, or groundwater aquifer prior to reuse, such as in groundwater recharge.
Potable water reuse	Use of highly treated reclaimed water to augment drinking water supplies.
Direct potable reuse	Incorporation of reclaimed water into a potable water supply system, without relinquishing control over the resource.
Indirect potable reuse	Incorporation of reclaimed water into a potable water supply by including an intermediate step in which reclaimed water is mixed with surface or groundwater sources upstream of intakes for drinking water treatment facilities.
Non-potable water reuse	Includes all water reuse applications other than direct or indirect use for drinking water supplies.

cilities. Some cities in Japan, including Tokyo, use reclaimed water for toilet flushing in high-rise office and commercial buildings (*10*).

To foster sustainability, the quality and quantity of water use must be linked to water availability. Cost-effective use of reclaimed water for industrial or irrigation applications necessitates producing it relatively close to the potential user. In addition, because requirements for irrigation tend to be seasonal whereas reclaimed water production is continuous, effective storage also is needed. One concept that is gaining acceptance is decentralized wastewater treatment facilities, which produce reclaimed water in locations that might be more readily accessible for use by industry or agriculture (*11*). This approach avoids the cost of transporting water to a central facility and then returning the reclaimed water to another location.



A summary of typical applications for reclaimed water is given in Table 1. Treatment goals are predicated on the basis of potential for human exposure to the reclaimed water and the availability of monitoring tools. For example, direct contact with reclaimed water is more likely in urban than industrial settings. However, it is impractical and cost-prohibitive to conduct extensive monitoring of all potential pathogens (viruses, bacteria, and protozoa). Thus, the quality of reclaimed water is monitored for "indicator" parameters, such as coliform bacteria and chlorine residuals.

Industrial recycling and reuse occur in industries such as power plants and pulp and paper production. For example, it has been estimated that about 10,000 gigawatts of new electrical generating capacity will be required worldwide by 2050 (*12*). The development of energy resources goes hand-in-hand with increasing urbanization. Freshwater is an essential resource for producing electricity because it is needed for applications such as high-purity steam, condensate cooling, and dust suppression. Although the net requirements depend on the distribution of energy sources (nuclear, fossil fuel, waste-to-energy, hydropower, solar, wind, etc.), water is always important.

At the same time, liquid discharges from industrial water users are subjected to increasingly stringent requirements in many locations. In the future, it is likely that many thermoelectric power generation facilities will have to comply with "zero liquid discharge" requirements to meet long-term watershed protection goals, particularly in environmentally sensitive locations. Thus, reclaimed water can provide a viable water source for thermoelectric power generation without the potential health risks associated with direct exposure to reclaimed water.

New challenges

Over the last half of the 20th century, the increasing availability of chemical products for industrial, medical, and household uses resulted in subtle but consistent changes in the characteristics of the wastewater that is produced in urban environments. Although pharmaceuticals and industrial chemicals have dramatically improved quality of life worldwide, the presence of residual materials and byproducts in reclaimed water has introduced new challenges to the engineering community. Because reclaimed water is produced from treated wastewater, the ability to control the quality of the final product is important.

Technologies exist that can purify or re-purify water to distilled water quality. However, treatment costs are related to the characteristics of the wastewater. In addition, as more information about the prevalence of new contaminants emerges, current assessment tools may become obsolete.

Control of trace contaminants

The underlying premise of wastewater treatment is a commitment to remove pollutants from water. The removal efficiency of a given treatment technology is assessed by comparing the concentrations of contaminants before and after treatment. Thus, control of individual constituents can only be assessed if reliable monitoring techniques are available. Currently, the characteristics of organics in reclaimed water are measured using nonspecific parameters such as biochemical oxygen demand (BOD) or total organic carbon (TOC). The residual organic carbon in reclaimed water ranges from 2 to 10 milligrams per liter. Efforts to characterize the residual organic carbon have focused on the quantification of hydrophobic and hydrophilic fractions; molecular size analysis; and the identification of specific constituents such as pesticides, industrial and pharmaceutical chemicals, and other persistent pollutants. However, even by applying sophisticated analytical chemistry techniques, it is only possible to quantify about 10% of the residual organic carbon in reclaimed water (*13*).

As new types of chemicals are introduced into the waste stream, the water reclamation community finds itself fighting an elusive battle to address new and emerging contaminants of concern. Currently, a gap exists between what analytical methodology can detect and the composition of reclaimed water, partic-

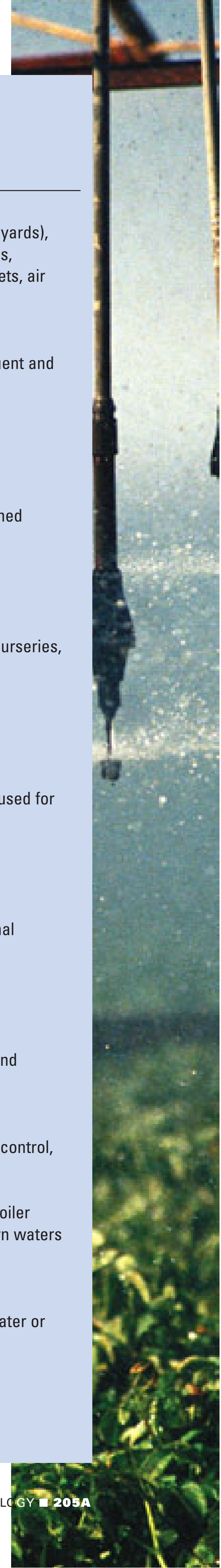
TABLE 1

Applications for using reclaimed water

Water reuse	Treatment goals[a, b]	Examples of applications
Urban use		
Unrestricted	Secondary, filtration, disinfection BOD_5: ≤10 mg/L Turbidity: ≤2 NTU Fecal coliform: ND/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Landscape irrigation (parks, playgrounds, school yards), fire protection, construction, ornamental fountains, recreational impoundments, in-building uses (toilets, air conditioning)
Restricted-access irrigation	Secondary and disinfection BOD_5: ≤30 mg/L TSS: ≤30 mg/L Fecal coliform: ≤200/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Irrigation of areas where public access is infrequent and controlled (golf courses, cemeteries, residential, greenbelts)
Agricultural irrigation		
Food crops	Secondary, filtration, disinfection BOD_5: ≤10 mg/L Turbidity: ≤2 NTU Fecal coliform: ND/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Crops grown for human consumption and consumed uncooked
Non-food crops and food crops consumed after processing	Secondary, disinfection BOD_5: ≤30 mg/L TSS: ≤30 mg/L Fecal coliform: ≤200/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Fodder, fiber, seed crops, pastures, commercial nurseries, sod farms, commercial aquaculture
Recreational use		
Unrestricted	Secondary, filtration, disinfection BOD_5: ≤10 mg/L Turbidity: ≤2 NTU Fecal coliform: ND/100 mL Cl_2 residual: 1 mg/L; pH 6–9	No limitations on body contact (lakes and ponds used for swimming, snowmaking)
Restricted	Secondary, disinfection BOD_5: ≤30 mg/L TSS: ≤30 mg/L Fecal coliform: ≤200/100 mL Cl_2 residual: 1 mg/L; pH 6–9	Fishing, boating, and other noncontact recreational activities
Environmental enhancement	Similar to unrestricted urban uses Dissolved oxygen; pH 6–9 Coliform organisms; nutrients	Artificial wetlands, enhanced natural wetlands, and sustained stream flows
Groundwater recharge	Site-specific	Groundwater replenishment, salt water intrusion control, and subsidence control
Industrial reuse	Secondary and disinfection BOD_5: ≤30 mg/L TSS: ≤30 mg/L Fecal coliform: ≤200/100 mL	Cooling system makeup water, process waters, boiler feed water, construction activities, and washdown waters
Potable reuse	Meet requirements for safe drinking water; specific regulations do not exist and specific goals remain unresolved	Blending with municipal water supply (surface water or groundwater)

[a] Adapted from Ref. 26.

[b] BOD_5, biochemical oxygen demand; ND, not detected; NTU, nephelometric turbidity units; TSS, total suspended solids.



ularly with respect to analytes that could pose uncertain and potentially long-term health risks. The types of trace contaminants of concern in reclaimed water include microbial pathogens, industrial and pharmaceutical chemicals, residual home cleaning and/or personal care products (PCPs), salts, heavy metals, and other persistent pollutants. Microbial contaminants are controlled through engineered treatment systems coupled with assessment of indicator organisms. However, the absence of indicator organisms (total or fecal coliform) does not always correlate to the absence of viral or protozoan pathogens (*14*).

Recent studies in environmental toxicology and pharmacology have suggested that long-term health risks may be associated with chronic exposure to trace chemical compounds, such as pharmaceutically active compounds (PhACs), pesticides, PCPs, and disinfection byproducts (DBPs) in reclaimed water (*15–19*). Recently, many of these compounds have been classified as endocrine disrupters that can interfere with the functioning of natural hormones. Exposure to endocrine disrupters can impact the growth of amphibians, fish, and other wildlife at levels as low as parts per trillion (*17*).

Understanding the prevalence of these compounds and how to control them in the context of wastewater treatment is an active area of research. Some compounds, such as DBPs and *N*-nitrosodimethylamine, are formed during wastewater treatment, while other constituents are not removed completely by conventional wastewater treatment practices. Residues and metabolites of pharmaceutical compounds, including antibiotics, are also of concern when drinking water source is affected by water reuse activities.

In the long run, it is vital to society that a dialogue be established between the chemical industry and the environmental community to better control trace chemicals in reclaimed water. Instead of burdening wastewater reclamation plants with treating an array of unknown chemicals, chemical producers should bear some responsibility. Ultimately, if a chemical life-cycle analysis were an integral part of product development, more "environmentally friendly" pharmaceuticals, cleaning compounds, PCPs, and industrial chemicals could be created. It is much easier to prevent the release of contaminants into the waste stream than remove trace levels of compounds that have unknown health consequences and are difficult to measure, biodegrade, and treat.

Treatment technologies

Treatment technologies for reclaimed water are, for the most part, derived from physical, chemical, and biological processes used for municipal wastewater and drinking water. While conventional treatment practices produce water that meets existing regulatory standards, limited information is available on the effectiveness of these technologies for control of PhACs, PCPs, and other trace contaminants in reclaimed water.

Advanced technologies, such as membrane bioreactors, microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, could be effective for producing high-quality reclaimed water. Distillation can also successfully produce water that is free of nonvolatile organics, pathogens, and salts; however, it is only

TABLE 2

Summary of water quality parameters relevant to water reclamation and reuse

Parameter	Significance in wastewater reclamation	Approximate range in treated wastewater	Treatment goal in reclaimed water[a]
Organic indicators			
BOD_5	Organic substrate for microbial or algal growth	10–30 mg/L	<1–10 mg/L
Total organic carbon	Measure of organic carbon	1–20 mg/L	<1–10 mg/L
Total suspended solids (TSS)	Measure of particles in wastewater can be related to microbial contamination, turbidity; can interfere with disinfection effectiveness	<1–30 mg/L	<1–10 mg/L
Turbidity	Measure of particles in wastewater; can be correlated to TSS	1–30 NTU	<1–30 NTU
Nutrients			
Nitrogen	Nutrient source for irrigation; can also contribute to algal growth	10–30 mg/L	<1–30 mg/L
Phosphorus	Nutrient source for irrigation; can also contribute to algal growth	0.1–30 mg/L	<1–20 mg/L
Pathogenic organisms	Measure of risk of microbial infection due to enteric viruses, pathogenic bacteria, and protozoa	Coliform organisms: <1–1000/100 mL	<1–200/mL Other pathogens are controlled by treatment technology

[a] Treatment goal depends on specific water reuse application.

practical where sources of waste heat and energy are available, such as cooling or boiler water associated with thermoelectric power generation. Frequently, the application of advanced technologies requires more energy resources, which increases operational costs. Moreover, these technologies generate process residuals, such as reject water from membrane systems, that act to concentrate contaminants and thereby impose a disposal dilemma.

Monitoring tools

Treatment and monitoring requirements for reclaimed water vary depending on the intended use. Table 2 provides examples of water quality monitoring parameters routinely used to evaluate the quality of reclaimed water. Although these approaches are useful, more rapid and specific screening tools are needed to assess microbial and chemical quality. The application of biosensors and molecular biology techniques may help to provide "real-time" assessment of the prevalence of pathogens and the effectiveness of control measures.

Of particular concern is the need to improve our capability to quantify trace levels of organic substances in reclaimed water. The sensitivity of analytical instruments has improved significantly over the past decade, and it is now possible to detect parts-per-trillion levels of some compounds in reclaimed water (*20*). Enzyme-linked immunosorbent assays (ELISAs) are well-developed tools for screening of environmental pollutants. For some compounds, ELISA methods are highly sensitive but lack specificity. Nevertheless, ELISA and other types of enzyme or antibody-based assays provide relatively rapid screening tools (*21–23*). On the other hand, bulk chemical parameters, such as TOC, are measured in the parts-per-million range.

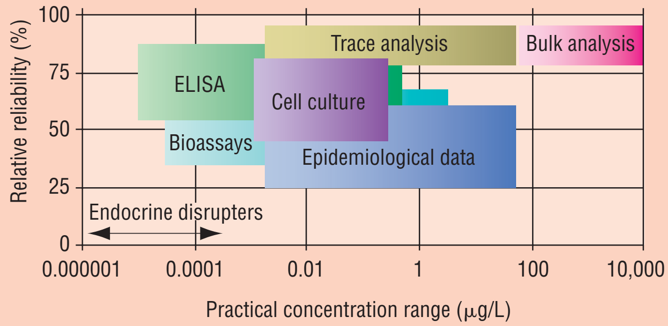
In comparison to analytical data, exposure-based approaches for health-risk analysis, such as bioassays, cell culture, and other in vitro and in vivo tests, provide data that can be correlated to potential health impacts but lack specific information on chemical composition. For example, Figure 2 shows many assays capable of detecting toxicity or providing evidence of endocrine-disrupting effects at concentration levels well below the currently available detection limits. Epidemiological data can provide direct information on health impacts for a specific population, either retrospectively or prospectively. But it is not always possible to obtain a comprehensive set of chemical data corresponding to epidemiological studies.

During the 1990s, extensive studies of potential health effects associated with exposure to reclaimed water were conducted in Tampa, Fla.; Denver, Colo.; and San Diego, Calif. (*7, 9*). Each study included a comprehensive suite of analytical tests and bioassays. In all of these studies, no adverse health effects were associated with exposure to reclaimed water versus other drinking water sources. However, as new and emerging contaminants are identified in reclaimed water and drinking water, it is important to remain vigilant and to optimize elimination or removal through source control coupled with effective water and wastewater treatment systems. To date, many of the compounds identified in reclaimed water have also been found in numerous drinking water sources (*9, 15, 20, 22*).

FIGURE 2

Analytical methods for trace organic compounds and endocrine disrupters

Various chemical and biological assays can detect trace organic compounds in water, but each method's detection limits and reliability differ. In lieu of exhaustive chemical monitoring, enzyme-linked immunosorbent assays (ELISAs) and in vivo and in vitro bioassays can detect the low-level effective ranges required to detect endocrine disrupters.

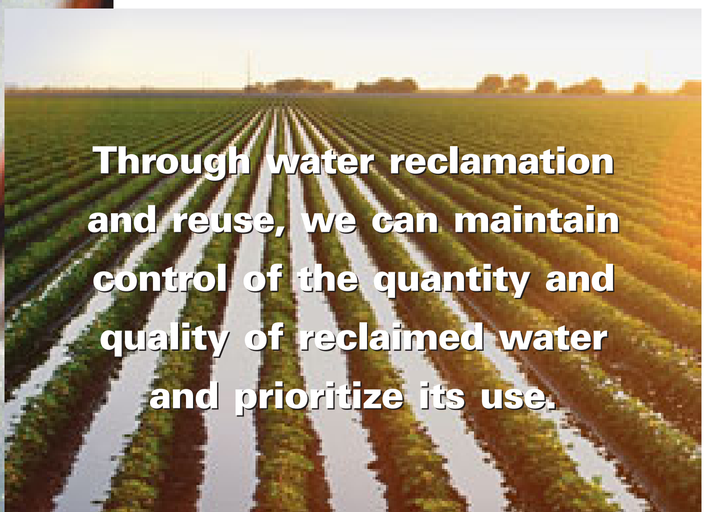


In reality, it is impossible to monitor every potential constituent in reclaimed water, so a rational approach is needed that takes into account inherent constraints associated with methodology, analytical sensitivity, costs, and turnaround time. The real challenge is to develop and implement sound, scientific, reliable, practical, and efficient monitoring tools for ensuring that minimal risks are associated with exposure to reclaimed water. In lieu of exhaustive chemical monitoring, bioassays (in vivo), cell cultures (in vitro), or biochemical techniques (ELISAs) can provide conservative information on potential acute and chronic health risks due to trace contaminants. Careful control of the use of reclaimed water, with an emphasis on non-potable applications, can help to minimize direct exposure while providing additional opportunities for degradation or removal of trace contaminants.

Dependable water supply

The need for a dependable water supply is crucial, particularly for large cities. As the population outgrows the existing water supply, supplemental sources must be developed. New sources may include water transfer from neighboring regions, internal water sources developed by optimizing the city's water use, water conservation, and water reclamation and reuse. As the size of cities and their populations expands, the quantity of wastewater increases proportionally. San Diego County in California is an example of projected changes in the distribution of water sources in an urban setting. Currently, about 90% of the municipal water supply is obtained from a wholesale water provider. In the future, as water demands increase in consort with growing development and urbanization, an estimated 60% of the water supply will be derived from wholesale sources (*24*). Increased use of re-

claimed water and desalination of seawater will have to make up the difference. At inland locations or where desalination would cost too much, reclaimed water may significantly contribute to the overall water supply. It may be used for irrigation or industry, and it can replenish groundwater and surface water resources.



The future of water reuse

Although there is a long history of reusing wastewater throughout the world, increasing urbanization, particularly in developing countries, is posing new water resource management challenges. Increasing pressures on freshwater resources is spurring water reuse, with significant activity in countries such as the United States, Mexico, Mediterranean countries, the Middle East, South Africa, Australia, Japan, China, and Singapore. However, the absence of an appropriate infrastructure to provide adequate treatment and delivery can hamper progress.

Through water reclamation and reuse, we can maintain control of the quantity and quality of reclaimed water and prioritize its use. Concerns for long-term health effects still exist with respect to trace chemical contaminants and emerging microbial pathogens, but reclaiming and reusing the water rather than discharging treated wastewater for disposal to the environment is critical for the development of sustainable water resources. The extent to which water is reused is intricately linked to health protection, engineering feasibility, public acceptance, and the perceived value of the water in the community. As a society, we no longer have the luxury of using water only one time; however, we have the responsibility of maintaining and ensuring water quality.

Audrey D. Levine is an associate professor of civil and environmental engineering at the University of South Florida, Tampa. Takashi Asano is Professor Emeritus in the Department of Civil and Environmental Engineering at the University of California, Davis, and was the 2001 recipient of the Stockholm Water Prize. Address correspondence regarding this article to Levine at levine@eng.usf.edu or Asano at tasano@ucdavis.edu.

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