WATER FROM (WASTE)WATER -- THE DEPENDABLE WATER RESOURCE

Takashi Asano
Department of Civil and Environmental Engineering
University of California at Davis,
Davis, CA 95616-2311, U.S.A.

Abstract

Water reclamation and reuse provides a unique and viable opportunity to augment traditional water supplies. As a multi-disciplined and important element of water resources development and management, water reuse can help to close the loop between water supply and wastewater disposal. Effective water reuse requires integration of water and reclaimed water supply functions. The successful development of this dependable water resource depends upon close examination and synthesis of elements from infrastructure and facilities planning, wastewater treatment plant siting, treatment process reliability, economic and financial analyses, and water utility management.

In this paper, fundamental concepts of water reuse are discussed including definitions, historical developments, the role of water recycling in the hydrologic cycle, categories of water reuse, water quality criteria and regulatory requirements, and technological innovations for the safe use of reclaimed water. The paper emphasizes the integration of this alternative water supply into water resources planning and the emergence of modern water reclamation and reuse practices from wastewater to reclaimed water to *repurified* water.

Keywords

Public health; treatment; water quality; water reclamation; water resources; water reuse

Introduction

Inadequate water supplies and water quality deterioration represent serious contemporary concerns for many municipalities, industries, agriculture, and the environment in various parts of the world. Several factors have contributed to these problems such as continued population growth in urban areas, contamination of surface water and groundwater, uneven distribution of water resources, and frequent droughts caused by extreme global weather patterns. For more than a quarter of a century, a recurring thesis in environmental

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and water resources engineering has been that it is feasible to treat wastewater to a high enough quality that it is a resource that could be put to beneficial use rather than wasted. By applying this conviction to responsible engineering, coupled with the vexing problems of increasing water shortages and environmental pollution, a realistic framework has emerged for considering reclaimed water as a water resource in many parts of the world. Thus, water reuse has been dubbed as the *greatest challenge of the 21st century* as water supplies remain finite and water demands increase because of escalating populations and per capita consumption. Water reuse accomplishes two fundamental functions: (1) the treated effluent is used as a water resource for beneficial purposes, and (2) the effluent is kept out of streams, lakes, and beaches; thus, reducing pollution of surface water and groundwater (Asano, 1998).

Water resources in developing countries in arid and semi-arid regions of the world with rapidly growing populations and limited economic resources need special attention. Wastewater treatment technologies for protecting public health and the environment in developing countries are often established in relation to the limited resources available for public works. Confined wastewater collection systems and wastewater treatment are often nonexistent in developing countries, and wastewater inadvertently provides an essential source for water and fertilizers. Unfortunately, in many water-scarce regions, untreated wastewater has traditionally been re-used without supplemental treatment; this practice should be stopped to prevent obvious environmental sanitation and public health problems. Planned water reuse in the context of integrated water resources management provides a strong argument against this traditional practice and offers instead systematic progress towards safe and reliable sanitation practices.

The foundation of water reuse is built upon three principles: (1) providing reliable treatment of wastewater to meet strict water quality requirements for the intended reuse application, (2) protecting public health, and (3) gaining public acceptance. Whether water reuse is appropriate for a specific locale depends upon careful economic considerations, potential uses for the reclaimed water, and the relative stringency of waste discharge requirements. Public policies can be implemented that promote water conservation and reuse rather than the costly development of additional water resources with considerable environmental expenditures. Through integrated water resources planning, the use of reclaimed water may provide sufficient flexibility to allow a water agency to respond to short-term needs as well as increase the reliability of long-term water supplies.

In the planning and implementation of water reuse, the intended water reuse applications govern the degree of wastewater treatment required and the reliability of wastewater treatment processing and operation. In principle, wastewater or any marginal quality waters can be used for any purpose as long as adequate treatment is provided to meet the water quality requirements for the intended use. The dominant applications for the use of reclaimed water include: agricultural irrigation, landscape irrigation, industrial recycling and reuse, and groundwater recharge. Among them, agricultural and landscape irrigation are widely practiced throughout the world with well-established health protection guidelines and agronomic practices.

Water reuse definitions

To facilitate communication among different groups associated with water reuse, it is important to understand the terminology used in the arena of water reclamation and reuse. *Wastewater reclamation* is the treatment or processing of wastewater to make it reusable, and *water reuse* is the use of treated wastewater for beneficial purposes such as agricultural irrigation and industrial cooling. *Reclaimed water* is a treated effluent suitable for an intended water reuse application. In addition, *direct* water reuse requires the existence of pipes or other conveyance facilities for delivering reclaimed water. *Indirect* reuse, through discharge of an effluent to receiving water for assimilation and withdrawals downstream, is recognized to be important but does not constitute *planned direct* water reuse. In contrast to direct water reuse, *water recycling* normally involves only one use or user and the effluent from the user is captured and redirected back into that use scheme. In this context, water recycling is predominantly practiced in industry (Metcalf & Eddy, 1991).

Historical perspective

Early developments in the field of water reuse are synonymous with the historical practice of land application for the disposal of wastewater. With the advent of sewerage systems in the nineteenth century, domestic wastewater was used at "sewage farms" and by 1900 there were numerous sewage farms in Europe and in the United States. While these sewage farms were used primarily for waste disposal, incidental use was made of the water for crop production or other beneficial uses. During the past century, the growing need for reliable water has resulted in the development of a number of water reclamation and reuse projects. Selected examples that depict the historic development of water reuse in different parts of the world are listed chronologically in Table 1.

Table 1 Selected examples of historic development of water reuse in different parts of the world

Year	Location	Water reuse examples
1912 - 1985	Golden Gate Park, San Francisco, California, U.S.A.	Watering lawns and supplying ornamental lakes.
1926	Grand Canyon National Park, Arizona, U.S.A.	Toilet flushing, lawn sprinkling, cooling water, and boiler feed water.
1929	City of Pomona, California, U.S.A.	Irrigation of lawns and gardens
1942	City of Baltimore, Maryland, U.S.A.	Metals cooling and steel processing at the Bethlehem Steel Company.
1960	City of Colorado Springs, Colorado, U.S.A.	Landscape irrigation for golf courses, parks, cemeteries, and freeways.

Year	Location	Water reuse examples
1961	Irvine Ranch Water District, California, U.S.A.	Irrigation, industrial and domestic uses, later including toilet flushing in high-rise buildings.
1962	County Sanitation Districts of Los Angeles County, California, U.S.A.	Groundwater recharge using spreading basins at the Montebello Forebay.
1962	La Soukra, Tunisia	Irrigation with reclaimed water for citrus plants and to reduce saltwater intrusion into groundwater.
1968	City of Windhoek, Namibia	Advanced direct wastewater reclamation system to augment potable water supplies.
1969	City of Wagga Wagga, Australia	Landscape irrigation of sporting fields, lawns, and cemeteries.
1970	Sappi Pulp and Paper Group, Enstra, South Africa	Industrial use of reclaimed municipal wastewater for pulp and paper processes.
1976	Orange County Water District, California, U.S.A.	Groundwater recharge by direct injection into the aquifers at Water Factory 21.
1977	Dan Region Project, Tel-Aviv, Israel	Groundwater recharge via basins. Pumped groundwater is transferred via a 100 km-long conveyance system to southern Israel for unrestricted crop irrigation.
1977	City of St. Petersburg, Florida, U.S.A.	Irrigation of parks, golf courses, schoolyards, residential lawns, and cooling tower make-up water.
1984	Tokyo Metropolitan Government, Japan	Water recycling project in Shinjuku District of Tokyo providing reclaimed water for toilet flushing in 19 high-rise buildings in highly congested metropolitan area.
1985	City of El Paso, Texas, U.S.A.	Groundwater recharge by direct injection into the Hueco Bolson aquifers, and power plant cooling water.
1987	Monterey Regional Water Pollution Control Agency, California. U.S.A.	Monterey Wastewater Reclamation Study for Agriculture -- agricultural irrigation of food crops eaten uncooked including artichoke, celery, broccoli, lettuce, and cauliflower.
1989	Shoalhaven Heads, Australia	Irrigation of gardens and toilet flushing in private residential dwellings
1989	Consorci de la Costa Brava, Girona, Spain	Golf course irrigation

Role of water recycling in the hydrologic cycle

The inclusion of planned water reclamation, recycling and reuse in water resource systems reflects the increasing scarcity of water sources to meet societal demands, technological advancements, increased public acceptance, and improved understanding of public health risks. As the link between wastewater, reclaimed water, and water reuse has become better understood, increasingly smaller recycle loops are possible. Traditionally, the hydrologic cycle has been used to represent the continuous transport of water in the environment. The water cycle consists of fresh-water and salt-water surface resources, subsurface groundwater, water associated with various land use functions, and atmospheric water vapor. Many sub-cycles to the hydrologic cycle exist including the engineered transport of water. Wastewater reclamation, recycling and reuse represent significant components of the hydrologic cycle in urban, industrial, and agricultural areas. A conceptual overview of the cycling of water from surface and groundwater resources to water treatment facilities, irrigation, municipal, and industrial applications, and to wastewater reclamation and reuse facilities is shown in Figure 1.

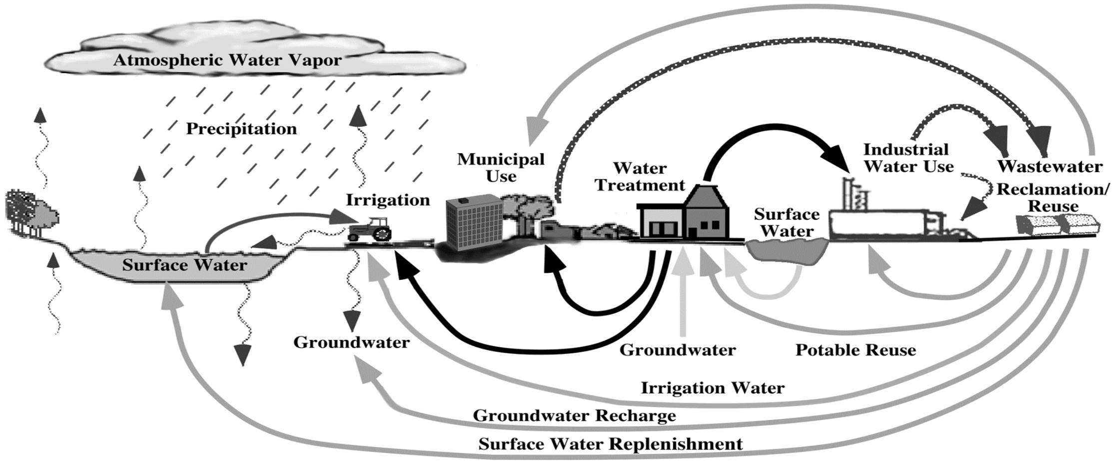

Figure 1 The role of engineered treatment, reclamation, and reuse facilities in the cycling of water through the hydrologic cycle (After Asano and Levine, 1995)

The major pathways of water reuse include irrigation, industrial use, surface water replenishment, and groundwater recharge. Surface water replenishment and groundwater recharge also occur through natural drainage and through infiltration of irrigation and storm water runoff. The potential use of reclaimed water for potable water sources is also shown in Figure 1. The quantity of water transferred via each pathway depends on the watershed characteristics, climatic and geo-hydrologic factors, the degree of water utilization for various purposes, and the degree of direct or indirect water reuse.

The water used or reused for agricultural and landscape irrigation includes agricultural, residential, commercial, and municipal applications. Industrial reuse is a general category encompassing water use for a diversity of industries that include power plants, pulp and paper, and other industries with high rates of water utilization. In some cases, closed-loop recycle systems have been developed that treat water from a single process stream and recycle the water back to the same process with some make-up water. In other cases, reclaimed municipal water is used for industrial purposes such as in cooling towers. The National Aeronautical Space Administration (NASA) has studied closed-loop systems for long-duration space missions and space stations.

Categories of water reuse

In the planning and implementation of water reclamation and reuse, the reclaimed water application will usually govern the type of wastewater treatment needed to protect public health and the environment, and the degree of reliability required for each sequence of treatment processes and operations. From a global perspective, water reuse applications have been developed to replace or augment water resources for specific applications, depending on local water use patterns. In general, water reuse applications fall under one of seven categories: (1) agricultural irrigation, (2) landscape irrigation, (3) groundwater recharge, (4) industrial reuse, (5) environmental and recreational uses, (6) non-potable urban uses, and (7) indirect or direct potable reuse. The relative amount of water used in each category varies locally and regionally due to differences in specific water use requirements and geopolitical constraints.

- **Agricultural irrigation** represents the largest current use of reclaimed water throughout the world. This reuse category offers significant future opportunities for water reuse in both industrialized countries and developing countries.
- **Landscape irrigation** is the second largest user of reclaimed water in industrialized countries and it includes the irrigation of parks; playgrounds; golf courses; freeway medians; landscaped areas around commercial, office, and industrial developments; and landscaped areas around residences. Many landscape irrigation projects involve dual distribution systems, which consist of one distribution network for potable water and a separate pipeline to transport reclaimed water.
- **Industrial activities** represent the third major use of reclaimed water, primarily for cooling and process needs. Cooling water creates the single largest industrial demand for water and as such is the predominant industrial water reuse either for cooling towers or cooling ponds. Industrial uses vary greatly and water quality requirements tend to be industry-specific. To provide adequate water quality, supplemental treatment may be required beyond conventional secondary wastewater treatment.
- **Groundwater recharge** is the fourth largest application for water reuse, either via spreading basins or direct injection to groundwater aquifers. Groundwater recharge includes groundwater replenishment by assimilation and storage of reclaimed water in groundwater aquifers, or establishing hydraulic barriers against salt-water intrusion in coastal areas.
- **Recreational and environmental uses** constitute the fifth largest use of reclaimed water in industrialized countries and involve non-potable uses related to land-based water features such as the development of recreational lakes, marsh enhancement, and stream flow augmentation. Reclaimed water impoundments can be incorporated

into urban landscape developments. Man-made lakes, golf course storage ponds and water traps can be supplied with reclaimed water. Reclaimed water has been applied to wetlands for a variety of reasons including: habitat creation, restoration and/or enhancement, provision for additional treatment prior to discharge to receiving water, and provision for a wet weather disposal alternative for reclaimed water.

- **Non-potable urban uses** include fire protection, air conditioning, toilet flushing, construction water, and flushing of sanitary sewers. Typically, for economic reasons, these uses are incidental and depend on the proximity of the wastewater reclamation plant to the point of use. In addition, the economic advantages of urban uses can be enhanced by coupling with other ongoing reuse applications such as landscape irrigation.
- **Potable reuse** is another water reuse opportunity, which could occur either by blending in water supply storage reservoirs or, in the extreme, by direct input of highly treated wastewater into the water distribution system. Although the likelihood of implementing this option in the United States is remote, a successful example includes the City of Windhoek, Namibia (Harhoff and van der Merwe, 1996) as shown in Table 1.

Spectrum of reclaimed water quality

As water is used for various applications, the quality changes due to introduction of various constituents. A conceptual comparison of the extent to which water quality changes through municipal applications is shown in Figure 2. Water treatment technologies are applied to produce high quality drinking water that meets applicable federal and state or international standards for domestic (drinking) water supply. Conversely, municipal and industrial water use tends to degrade water quality by introducing chemical or biological contaminants. The quality changes necessary to upgrade the wastewater then become the basis for wastewater treatment. In practice, treatment is carried out to the point required by regulatory agencies for protection of the aquatic environment and other beneficial uses. The dashed line in Figure 2 represents an increase in treated water quality as necessitated by water reuse. Ultimately, as the quality of treated water approaches that of unpolluted natural water, the practical benefits of water reclamation and reuse are evident. As more advanced technologies are applied for water reclamation, such as carbon adsorption, advanced oxidation, and reverse osmosis, the quality of reclaimed water can exceed conventional drinking water quality by most conventional parameters, and it is termed *repurified* water. Today, technically proven water reclamation or water purification processes exist to provide water of almost any quality desired.

Water quality criteria and regulatory requirements

To protect public health without unnecessarily discouraging water reuse, regulatory approaches stipulate water quality standards in conjunction with requirements for treatment, sampling, and monitoring. With reclaimed water, as in many activities, a key concern is the potential risk of human exposure to pathogenic organisms. However, controlling the extent of human exposure to the reclaimed water and ensuring that the wastewater treatment system is effective and reliable can minimize health impacts.

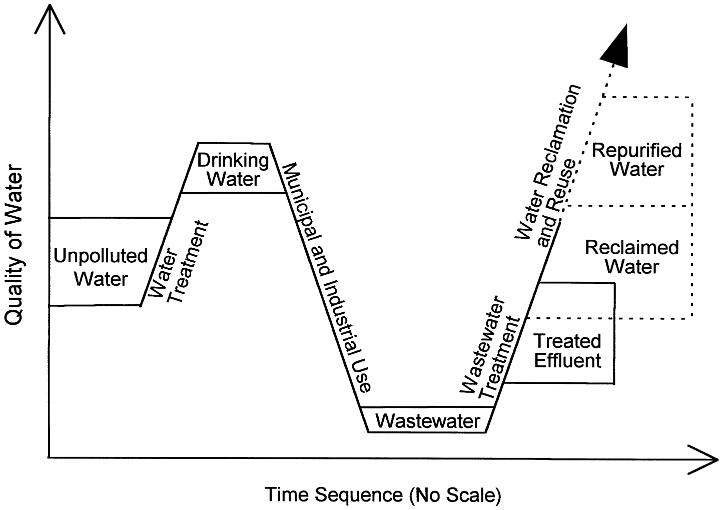

Figure 2 Water quality changes during municipal uses of water in a time sequence

In the United States, comprehensive federal standards for water reuse do not exist; thus, water reclamation criteria are developed by individual states, often in conjunction with regulations addressing land treatment and disposal of wastewater. Some of the major differences among the approaches taken by individual states are associated with degree of specificity provided in the rules. The degree of treatment required and the associated monitoring requirements tend to be related to the specific water reuse application. In general, irrigation systems are categorized according to the potential degree of human exposure. To produce reclaimed water that is virtually pathogen-free, a higher degree of treatment is required for irrigation of crops that are consumed uncooked, or when reclaimed water is used for irrigation of locations that are likely to have frequent human contact.

The World Health Organization guidelines (WHO, 1989) emphasize that a series of wastewater stabilization ponds is necessary to meet microbial water quality requirements. Microbiological monitoring requirements also vary considerably among different jurisdictions: the WHO guidelines require monitoring of intestinal nematodes; whereas the California criteria rely on reliable wastewater treatment systems and monitoring of the total coliform density for assessment of microbiological quality. The main concerns for water reuse in the United States are the elimination of enteric viruses and emerging bacterial and protozoan pathogens. For most developing countries, the greatest concerns associated with the use of wastewater for irrigation are to prevent exposure to enteric *helminths* such as hookworm, *ascaris*, *trichuris*, and under certain circumstances, the beef tapeworm. These pathogens can damage the health of the general public consuming the crops irrigated with untreated or partially treated wastewater. In addition, sewage farm workers and their families may experience more serious health risks.

Health risk assessment for water reuse

Despite a long history of water reuse in many parts of the world, the question of *safety* of water reuse is still difficult to define and delineation of *acceptable* health risks have been hotly debated. In less developed countries where advanced levels of wastewater treatment are not possible or economically out of reach, a number of investigators have sought to assess the risk of using reclaimed water of varying quality in different reuse applications by controlling possible transmission routes of excreta-related infections. The WHO guidelines are an example of recognizing the fact that high concentrations of pathogens can exist in wastewater and partially treated effluents.

In addition to regulatory approaches, quantitative microbial risk assessments have been applied to provide a more rigorous assessment of health risks associated with various water reuse applications. In the United States, enteric viruses have received the most attention because of their low-dose infectivity, long-term survival in the environment, monitoring difficulties, and the limited extent of removal and inactivation that occurs in conventional wastewater treatment.

Health risks associated with exposure to enteric viruses in reclaimed water were analyzed using a quantitative microbial risk assessment approach (Asano, *et al.*, 1992; Tanaka, *et al.,* 1998). Monitoring data from four wastewater treatment facilities in California on enteric virus concentrations in unchlorinated secondary effluents were used as baseline data for the risk analysis. To assess potential health risks associated with the use of reclaimed water in various reuse applications, four exposure scenarios were tested: (1) golf course irrigation, (2) food crop irrigation, (3) recreational impoundments, and (4) groundwater recharge. Because enteric virus concentrations in unchlorinated secondary effluents were found to vary over a wide range, it was essential to characterize their variability. Two concepts related to the safety of water reuse were used: (1) the *reliability*, defined as the probability that the risk of infection does not exceed an acceptable risk, and (2) the *expectation*, defined by specifying an acceptable annual risk in which exposure to the enteric viruses may be estimated stochastically by numerical simulation such as Monte Carlo methods. The U.S. EPA Surface Water Treatment Rule (SWTR) (U.S. EPA, 1989) defines an acceptable risk as less than or equal to one pathogen-derived infection per 10,000 population per year from use of a public water supply. Therefore, if a 10^{-4} annual risk of infection (less than or equal to one infection per 10,000 population per year) is set as an acceptable risk for water reuse, the reliability can be calculated as the percent of time that infection risk due to exposure to enteric viruses in reclaimed water is less than the acceptable risk. Reliability estimations for each exposure scenario are presented in Table 2.

From the results of the analysis presented in Table 2, the reliability or relative safety of water reuse can be assessed in comparison to domestic water supplies that meet the SWTR. When the disinfected, filtered secondary effluent (tertiary treatment) is chlorinated at about 10 mg/L, there is virtually no difference in the probability of enteric virus infection whether reclaimed water or domestic water is used for golf course irrigation, crop irrigation, and groundwater recharge. However, depending on the water quality of the secondary effluent, there is a considerable difference in health risks associated with exposure to recreational impoundments where body contact sports and swimming may take place. Similar observations can be made for the use of chlorinated secondary effluent and the reclaimed water from contact filtration with chlorine doses of below 5 mg/L.

Table 2 Reliability of various water reuse applications meeting the criterion of one enteric virus infection per 10,000 population per year

Treatment process	**Secondary effluent from plant**	**Reliability, %**			
		Golf course Irrigation	**Crop irrigation**	**Recreational impoundment**	**Groundwater recharge**
Full treatment or contact filtration with 10 mg/L chlorine dose achieving 5.2 log removals of viruses	A	100	100	77	100
	B	100	100	99	100
	C	100	100	98	100
	D	99	100	62	100
Chlorination of secondary effluent with 5 mg/L chlorine achieving 3.9 log removals of viruses	A	95	100	10	100
	B	100	100	81	100
	C	99	100	93	100
	D	84	100	11	100
Contact filtration with 5mg/L chlorine dose achieving 4.7 log removals of viruses	A	100	100	48	100
	B	100	100	96	100
	C	100	100	97	100
	D	97	100	39	100

Adapted from Tanaka, *et al.*, 1998.

Cost of water reclamation and reuse

Reported water reclamation costs range widely. It is, therefore, important in comparing costs that differences in assumptions and factors associated with allocation of costs among wastewater treatment, and water reclamation and reuse be correctly understood. Although costs associated with secondary treatment of wastewater are often considered to be pollution control costs in industrialized countries, they serve as a baseline cost for comparison with tertiary and/or advanced treatment facilities for water reuse. A construction cost breakdown for various treatment processes within a secondary treatment system is estimated on the basis of 3,785 m^3/d with the total capital cost ($0.5/$m^3$) distributed as: primary treatment 24 %, secondary treatment 40%, sludge treatment 22%, and control, laboratory, and maintenance buildings 14% (based on the total capital cost of secondary treatment system in California).

A common misconception in planning for water reclamation and reuse is that reclaimed water represents a low-cost new water supply. This assumption is generally true only when water reclamation facilities are conveniently located near large agricultural or industrial users and when no additional treatment is required beyond the existing water pollution control facilities from which reclaimed water is delivered. The conveyance and distribution systems for reclaimed water represent the principal cost of most water reuse projects. Recent experience in California indicates that approximately 4 million U.S. dollars in capital cost are required for each 1 million m^3 per year of reclaimed water that are made available for reuse. Assuming a facility life of 20 years and 9 percent interest rate, the amortized cost of this reclaimed water is about $\$0.50/m^3$, excluding operation and maintenance costs. This reclaimed water is normally too expensive for traditional agricultural irrigation in the United States and most other countries; only landscape irrigation and other urban applications can afford to pay for the water.

As shown in Table 1, water reuse in Japan is directed toward urban reuse where higher costs can be borne for reclaimed water. The reported production cost for reclaimed water in Fukuoka City is $\$2.0/m^3$ compared to the drinking water cost of $\$1.9/m^3$. The price to consumers for reclaimed water averaged $\$3.0/m^3$ compared to the drinking water price of $\$3.7/m^3$. Even with a small margin for the reclaimed water used for toilet flushing in commercial buildings and apartment complexes, Fukuoka City has been able to produce a slight profit for its water reclamation and reuse systems (Ogoshi, *et al.,* 2000). Determined efforts by city officials were needed, however, to expand service areas and renovate commercial buildings in the downtown areas. Judging from this experience of more than 20 years, water reuse for toilet flushing can be economically justified in many water-scarce urban areas. Furthermore, reclaimed water can be justified more easily for new applications of water such as newly created parks and playgrounds, golf courses, and *water amenities* in urban redevelopment. Another reason for expensive water recycling in Japan is the expense associated with the installation of in-building dual distribution systems as well as the cost of installing pipelines in built-up and congested areas. These reclaimed water prices reflect competition for new water resources and these expenses are the necessary cost of doing business in highly urbanized metropolitan areas.

Costs are significantly affected by the fraction of utilization of a facility over the course of a year. Economic assumptions of useful lives and interest rates affect the amortization of capital costs embedded in unit costs. In some cases, reported costs may represent current expenses for old facilities and do not reflect costs to construct those facilities at today's prices. One factor that appears to significantly affect costs is the degree of utilization of available capacity in the treatment plant. Maximum utilization can be achieved by: (1) seasonal storage of effluent to compensate seasonal slack in water reuse demands, (2) obtaining a mix of reclaimed water uses to reduce seasonal peaks in demand, or (3) using alternative water supplies for meeting peak water demands.

Future directions for water reuse

In many parts of the world, agricultural irrigation using reclaimed water has been practiced for many centuries. Landscape irrigation such as irrigation of golf courses, parks and playgrounds has been successfully implemented in many urban areas for over 30 years. Salt management in irrigated croplands may require special attention in many arid and semi-arid regions. Beyond irrigation and non-potable urban reuse, indirect or direct potable reuse need careful evaluation and close public scrutiny. It is obvious from public health and acceptance standpoints that non-potable water reuse options must be exhaustively explored prior to any notion of indirect or direct potable reuse.

Groundwater recharge with reclaimed water and direct potable water reuse share many of the public health concerns encountered in drinking water withdrawn from polluted rivers and reservoirs. Three classes of constituents are of special concern where reclaimed water is used in such applications: (1) enteric viruses and other emerging pathogens; (2) organic constituents including industrial and pharmaceutical chemicals, residual home cleaning and personal care products and other persistent pollutants; and (3) salts and heavy metals. The ramifications of many of these constituents in trace quantities are not well understood with respect to long-term health effects. For example, there are concerns about exposure to chemicals that may function as endocrine disruptors; also the potential for development of antibiotic resistance is of concern. As a result, regulatory agencies are proceeding with extreme caution in permitting water reuse applications that affect potable water supplies. In each case in the United States where potable water reuse has been contemplated, alternative sources of water have been developed in the ensuing years and the need to adopt direct potable water reuse has been avoided. As the proportional quantities of treated wastewater discharged into the receiving water increases, much of the research which addresses groundwater recharge and potable water reuse is becoming of equal relevance to *unplanned indirect potable reuse* such as municipal water intakes located downstream from wastewater discharges or from increasingly polluted rivers and reservoirs. Examples include New Orleans, Louisiana on the Mississippi River and the Rhine Valley communities along the Rhine River in Germany and the Netherlands.

Reclaimed water is a locally controllable water resource that exists right at the doorstep of the urban environment, where water is needed the most and priced the highest. Closing the loop of the water cycle not only is technically feasible in industries and municipalities but also makes economic sense. While potable reuse is still a distant possibility and may never be implemented except under extreme conditions, groundwater recharge with advanced wastewater treatment technologies is a viable option backed by the decades of experience in Arizona, California, New York, and Texas as well as in Australia, Israel, Germany, the Netherlands, and the United Kingdom. Water reuse has become an essential element of future water resources development in integrated water resources management; thus, our opportunities and challenges will continue well into the 21st century.

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