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Water Reuse via Groundwater Recharge

Takashi Asano[a]

Sustainable water resources management emphasizes whole-system solutions to meet the water needs of present and future generations reliably and equitably. To increase the reliability of water supply, the artificial recharge of groundwater basins is becoming increasingly important where conjunctive use of surface water and groundwater resources is considered. Among the several sources of available water for groundwater recharge—which includes direct precipitation, flood or other surplus water, imported water, and reclaimed water—increasing attention has been given in recent years to the use of highly treated, reclaimed municipal wastewater as source water for groundwater recharge. The availability of reclaimed water for reuse at relatively low incremental cost and its dependability as a source of water even in a drought year are primary reasons for its consideration in groundwater recharge. This paper discusses an emerging field of water reuse via groundwater recharge.

Keywords: Groundwater recharge, Health effects, Wastewater, Water resources, Water reuse.

1. Introduction

Projections of continuing population growth, mostly in urban areas, have fueled global concerns about the ability to provide water in adequate quantity and quality in an increasingly complex environmental, economic, and social setting. Some of the important questions and concerns are as follows: (1) How long will existing water sources last? (2) What water sources can be relied upon? (3) Where will the next generation of water sources be found for rapidly growing cities as well as for agriculture and industries? (4) How will the conflict of watershed interests and beneficial uses be resolved? As a consequence of the social, economic, and environmental impacts of past water resources development and inevitable prospects of water scarcity expressed above, a shift is now occurring in the way water resources systems are planned, constructed, and managed.

2. Important role of water reuse

Water reuse involves considerations of water supply and public health, and also requires close examination of infrastructure and facilities planning, wastewater treatment plant siting, and treatment process reliability. Also important are economic and financial analyses and water utility management involving effective integration of water resources and reclaimed water. Although the immediate drivers behind water reuse may differ in each case, the overall goal is to close the hydrologic cycle on a much smaller, local scale. In this way, municipal wastewater, after proper treatment, becomes a valuable water resource literally "at the doorstep of the community" instead of being a waste to be disposed. An

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[a] Professor Emeritus, Department of Civil and Environmental Engineering, University of California at Davis, CA, U.S.A.

important breakthrough in the evolution of sustainability for water resources was achieved when water reuse was introduced as an option to satisfy water demand. Water reclamation and reuse is also the most challenging option, technically and economically, because these sources of water (i.e., municipal wastewater) are normally of the lowest quality. As a result, advanced treatment is commonly used, often beyond pure requirements stemming from the final water use, in order to alleviate any health concerns and make the water reuse option palatable to the public. The requirements for reclaimed water (e.g., advanced treatment and a separate distribution system) make water reuse costly, thus limiting its wider use. Through integrated water resources planning, however, the use of reclaimed water may provide sufficient flexibility to allow a water supply agency to respond to short-term needs as well as increase long-term water supply reliability without construction of dams and reservoirs at substantial economic and environmental cost.

Whether water reuse will be appropriate depends upon careful economic considerations, potential uses for the reclaimed water, stringency of waste discharge requirements, and public policy, where the desire to conserve rather than develop available water resources may override economic, esthetic, and public health considerations. In addition, the varied interests of many stakeholders, including those representing the environment, must be considered.

There are a number of factors that affect the implementation of water reuse. Historically, the impetus for water reuse has risen from three prime motivating factors: (1) availability of high-quality effluent, (2) increasing cost of freshwater development, and (3) desirability of establishing comprehensive water resources planning and management, including water conservation, water reuse, and environmental protection. Water reclamation and reuse can serve several objectives. Many benefits of water reclamation and reuse have been identified. Rationale for water reuse, potential benefits, and driving factors are summarized in the following.[1]

2.1. Rationale for water reclamation and reuse

- Water is a limited resource. Increasingly, society no longer has the luxury of using water only once.
- Water reclamation and reuse more appropriately matches water use application with water resource quality, resulting in more effective and efficient use of water.
- The goal of water resource sustainability is more attainable when the water reclamation and reuse option is implemented.

2.2. Potential benefits of water reclamation and reuse

- Water reclamation and reuse conserves freshwater supplies. It increases the total available water supply, and high-quality water supplies, such as for drinking water, can be conserved by substituting reclaimed water where appropriate.
- It is environmentally responsible. It can preserve the health of waterways, wetlands, flora and fauna, and reduce the level of nutrients and other pollutants entering waterways and sensitive marine environments by reducing effluent discharges.

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[1] Compiled from various sources, including Queensland Water Recycling Strategy (2001) and Mantovani et al. (2001).

- It makes economic sense. Reclaimed water is available near urban development where water supply reliability is most crucial and water is priced the highest.
- It can save resources. Reclaimed water originating from treated effluent contains nutrients. If this water is used to irrigate agricultural land, then less fertilizer is required for crop growth. By reducing nutrient (and resulting pollution) flows into waterways, tourism and fishing industries are also helped.

2.3. Factors driving further implementation of water reclamation and reuse

- **Proximity.** Reclaimed water is readily available in the vicinity of the urban environment, where water resources are most needed and are highly priced.
- **Dependability.** Reclaimed water provides a reliable water source, even in drought years, as production of urban wastewater remains nearly constant.
- **Versatility.** Technically and economically proven wastewater treatment processes are available now that can provide water for non-potable use and even for potable reuse.
- **Safety.** Non-potable water reuse systems have been in operation for over four decades with no documented adverse public health impacts in the United States or other developed countries.
- **Competing demands for water resources.** Pressure on existing water resources is increasing due to population growth and increased agricultural demand.
- **Fiscal responsibility.** Recognition is growing among water and wastewater managers of the economic and environmental benefits of using reclaimed water.
- **Public interest.** Awareness of the environmental impacts associated with overuse of water supplies is increasing, as is community enthusiasm for the concept of water reclamation and reuse.
- **Environmental and economic impacts of traditional approaches to managing water resources.** There is greater recognition of the environmental and economic costs of water storage facilities such as dams and reservoirs.
- **Proven track record.** The number of successful water reclamation and reuse projects throughout the world continues to grow.
- **More accurate cost of water.** New water charging arrangements introduced (such as full-cost pricing) more accurately reflect the full cost of delivering water to consumers, and use of these charging arrangements is growing.
- **More stringent water quality standards.** Increased costs are associated with upgrading wastewater treatment facilities to meet higher water quality requirements for effluent disposal.
- **Necessity and opportunity.** Motivating factors for development of water reclamation and reuse projects include droughts, water shortages, prevention of seawater intrusion, and restrictions on wastewater effluent discharges, plus economic, political, and technical conditions favorable to water reclamation and reuse.

3. Types of water reuse

The principal categories of water reuse applications for reclaimed water originating from treated municipal wastewater are shown in table 1 in descending order of projected volume of use. The majority of water reuse projects is for non-potable applications such as agricultural and landscape irrigation and industrial recycling and reuse. Groundwater recharge with reclaimed water can be designed for indirect potable reuse by replenishing groundwater.

Table 1. Water reuse categories and typical applications

Category	Typical application
Agricultural irrigation	- Crop irrigation - Commercial nurseries
Landscape irrigation	- Parks - Schoolyards - Freeway medians - Golf courses - Cemeteries - Greenbelts - Residential
Industrial recycling and reuse	- Cooling water - Boiler feed - Process water - Heavy construction
Groundwater recharge	- Groundwater replenishment - Saltwater intrusion control - Land subsidence control
Recreational/environmental uses	- Lakes and ponds - Marsh enhancement - Streamflow augmentation - Fisheries - Snowmaking
Non-potable urban uses	- Fire protection - Air conditioning - Toilet flushing
Potable reuse	- Blending in water supply reservoirs - Blending in groundwater - Direct pipe-to-pipe water supply

4. Treatment and technology needs

An important determinant of the potential applications and treatment requirements for water reuse is the quality of water resulting from various municipal uses. A conceptual comparison of the extent to which water quality changes through municipal applications is illustrated in figure 1. Water treatment technologies are applied to source water, such as surface water or groundwater, to produce drinking water that meets applicable standards for domestic (drinking) water supply. Conversely, municipal water uses degrade water quality by picking up chemical or biological contaminants and other constituents. The quality changes necessary to upgrade the resulting 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 environment, including protecting aquatic ecosystems and preservation of beneficial uses of receiving waters.

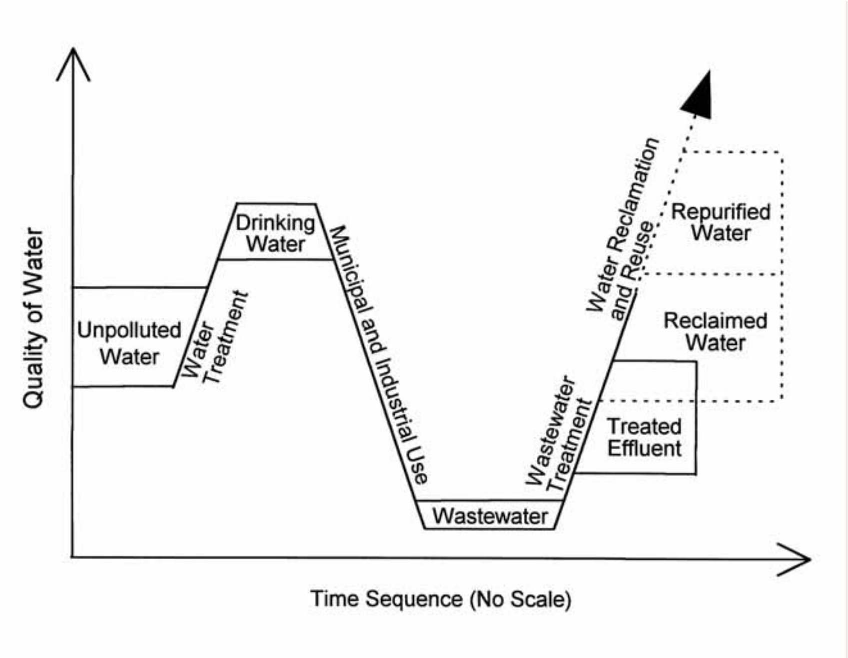

Figure 1. Water quality changes during municipal uses of water in a time sequence and the concept of water reclamation and reuse

The dashed line in figure 1 represents an increase in treated water quality as necessitated by water reuse. As the quality of treated water approaches that of unpolluted natural water, the practical benefits of water reclamation and reuse become evident. The levels of treatment and the resultant water quality endow the water with economic value as a water resource. As more advanced technologies are applied for water reclamation—such as carbon adsorption, advanced oxidation, and membrane technologies—the quality of reclaimed water can meet or exceed the conventional drinking water quality standards by all measurable parameters. This high-quality water for indirect potable reuse was termed *repurified* water in the case of San Diego (California) and *NEWater* in the case of Singapore. Today, technically proven water reclamation or water purification processes exist to provide water of almost any quality desired, including ultra-pure water for certain industrial and medical uses.

5. Groundwater recharge with reclaimed water

To increase the reliability of water supply, artificial recharge of groundwater basins is becoming increasingly important where conjunctive use of surface water and groundwater resources is considered. Major beneficial uses of groundwater include municipal water supply, agricultural and landscape irrigation, and industrial water supply. The natural recharge to the groundwater body includes deep percolation from precipitation, seepage from streams and lakes, and subsurface underflow. Natural replenishment of groundwater occurs very slowly, however, and thus excessive exploitation and mining of groundwater at greater than the rate of replenishment causes declining groundwater levels in the long term and leads to eventual exhaustion of the groundwater resource.

The following have been the main purposes of groundwater recharge: (1) to reduce, stop, or even reverse declines of groundwater levels; (2) to protect underground freshwater in coastal aquifers against saltwater intrusion; and (3) to store surface water for future use, including flood or other surplus water and reclaimed municipal wastewater. Groundwater recharge is also incidentally achieved in irrigation and land treatment and disposal of municipal and industrial wastewater via percolation and infiltration (Bouwer 1978; Todd 1980; Asano and Wassermann 1980; Asano 1985; WHO 2003).

There are several advantages to storing water underground via groundwater recharge, including the following:

1. The cost of artificial recharge may be less than the cost of equivalent surface water reservoirs.
2. The aquifer serves as an eventual natural distribution system and may eliminate the need for transmission pipelines or canals for surface water.
3. Water stored in surface reservoirs is subject to evaporation, potential taste and odor problems due to algae and other aquatic productivity, and to pollution, which may be avoided by soil-aquifer treatment (SAT) and underground storage.
4. Suitable sites for surface water reservoirs may not be available or may not be environmentally acceptable.

Among several sources of available water for groundwater recharge—including direct precipitation, flood or other surplus water, imported water, and reclaimed water—increasing attention has been given in recent years to the use of highly treated municipal wastewater (reclaimed water) as source water for groundwater recharge. The availability of reclaimed water for reuse at relatively low incremental cost and its dependability as a source of water even in a drought year are primary reasons for its consideration for groundwater recharge. A wide spectrum of technical and health challenges must be carefully evaluated, however, before undertaking a planned groundwater recharge project. Potential health risk considerations have limited expanding the use of reclaimed water for groundwater recharge when a large portion of groundwater contains reclaimed water that may affect the domestic water supply.

Most of the research issues that address groundwater recharge and potable reuse are equally relevant to *unplanned* or *incidental* potable reuse, such as municipal drinking water intakes located downstream from wastewater discharges or from increasingly polluted rivers and surface water reservoirs. Tapping of polluted water sources for unplanned or incidental potable reuse in the absence of adequate treatment may expose people to unknown health risks not associated with protected water sources. Currently, these unresolved health concerns (similar to the drinking water drawn from polluted natural water sources) certainly exist for water reuse via groundwater recharge for potable purposes. Properly planned and managed water reuse projects can produce higher quality water than the unplanned reuse of water happening in many parts of the world.

6. Techniques for groundwater recharge

Two types of groundwater recharge are commonly used with reclaimed water: (1) surface spreading or percolation, and (2) direct aquifer injection.

6.1. Groundwater recharge by surface spreading

Surface spreading is the simplest, oldest, and most widely applied method of artificial recharge (Todd 1980). In surface spreading, recharge waters such as treated municipal wastewater percolate from spreading basins through the unsaturated soil and ground (vadose) zone. Infiltration basins are the most favored methods of recharge because they allow efficient use of space and require only simple maintenance. In general, infiltration rates are highest where soil and vegetation are undisturbed.

Where hydro-geological conditions are favorable, wastewater reclamation can be implemented relatively simply through the SAT process. The necessary treatment can often be obtained by the process of filtration as the wastewater percolates through the vadose zone and then some distance laterally through the aquifer. Recommended pretreatment for municipal wastewater for the SAT process includes primary treatment (or a stabilization pond) and dissolved air flotation. Pretreatment processes that leave high algal concentrations in the recharge water should be avoided, because algae can severely clog the soil of infiltration basins. While renovated wastewater from the SAT process is of much better water quality than the influent wastewater, it could be lower quality than the native groundwater. Thus, the SAT process should be designed and managed to avoid encroachment into the native groundwater and to use only a portion of the aquifer. The distance and transit time between infiltration basins and wells or drains should be as great as possible, usually at least 50–100 meters (m) and perhaps six months to have adequate SAT (Bouwer 1978). In recent years, however, tertiary treated wastewater via granular-medium filtration and ultraviolet (UV) disinfection is a preferred treatment of water for surface spreading.

The advantages of groundwater recharge by surface spreading include the following: (a) groundwater supplies may be replenished in the vicinity of metropolitan and agricultural areas where groundwater over-drafting is severe, and (b) surface spreading provides the added benefits of the treatment effect of soils and transporting facilities of aquifers.

6.2. Direct injection to groundwater aquifer

Direct subsurface recharge is achieved when water is placed directly into an aquifer. In direct injection, highly treated reclaimed water is pumped directly into the groundwater zone, usually into a well-confined aquifer. Groundwater recharge by direct injection is practiced (a) where groundwater is deep or where the topography or existing land use makes surface spreading impractical or too expensive, and (b) when direct injection is particularly effective in creating freshwater barriers in coastal aquifers against the intrusion of saltwater (Bouwer 1978; Todd 1980). In arid climates, where the practice of groundwater recharge is most imperative, recharge will occur through such means as dry riverbeds and spreading basins, and in most situations there will be an unsaturated zone between the surface and the aquifer.

Both in surface spreading and direct injection, locating the extraction wells as great a distance as possible from the spreading basins or the injection wells increases the flow-path length and the residence time of the recharged water. These separations in space and in time contribute to the mixing of the recharged water and the other aquifer contents, the opportunity for favorable biological and chemical transformations to occur, and to the loss of identity of the recharged water originating from municipal wastewater. The latter is an important consideration in successful reuse of treated municipal wastewater in order to facilitate public acceptance.

7. Water reuse via groundwater recharge

Approximately 60 million cubic meters per year (Mm^3/y) of reclaimed water are used as source water for groundwater recharge in California. Groundwater recharge constitutes about 12 percent of the total volume of reclaimed water use (State of California 2002). Three examples of groundwater recharge projects using reclaimed municipal wastewater are shown in table 2.

Table 2. Examples of groundwater recharge using reclaimed municipal wastewater

County Sanitation Districts of Los Angeles County (CSDLAC) Montebello Forebay groundwater recharge project	The planned use of reclaimed water for groundwater recharge in the Montebello Forebay began in 1962 with the completion of the Whittier Narrows Water Reclamation Plant, making this project the oldest planned indirect potable reuse project in California. Today, three water reclamation plants designed, built, and operated by the CSDLAC provide recycled water for spreading in the Rio Hondo and San Gabriel recharge basins. Initially, the plants provided disinfected secondary effluent (activated sludge) for spreading, but in 1978 all three plants were upgraded to tertiary treatment with the addition of filtration and chlorination/dechlorination. Recycled water produced by the water reclamation plants complies with the primary drinking water standard and meets total coliform and turbidity limits of 2.2/100 milliliters (mL) and 2 nephelometric units (NTU), respectively. Total organic carbon (TOC) levels in the groundwater range from non-detectable to about 2.6 milligrams per liter (mg/L). Soil-aquifer treatment provides additional organics removal during infiltration. The Whittier Narrows Water Reclamation Plant produces 57,000 m^3 per day (m^3/d); the San Jose Creek plant, 380,000 m^3/d; and the Pomona plant, 49,000 m^3/d. Nearly all of the Whittier Narrows plant's effluent is used for groundwater recharge in the Montebello Forebay. The San Jose Creek Water Reclamation Plant provides the majority of the recycled water for groundwater recharge. Approximately 132,000 m^3/d from the San Jose Creek Water Reclamation Plant is sent to percolation basins for groundwater recharge in the Montebello Forebay. Today, runoff, impounded water from the canyon dams, recycled water from three CSDLAC wastewater treatment plants, and imported surface water (from the Colorado River and California State Water Project) can be directed to spreading grounds at points along the length of the river for the purpose of groundwater recharge in the San Gabriel Valley and the coastal plain. The Rio Hondo Spreading Grounds has 231 hectares (ha) of spreading basins available for spreading, and the San Gabriel Coastal Spreading Grounds has 52 ha. Percolation also occurs in 54 ha of the unlined San Gabriel River channel. The Water Replenishment District of Southern California (the agency charged with managing groundwater levels and pumping in the basin) conducts an extensive groundwater-monitoring program associated with the groundwater recharge project.
Orange County Water District (OCWD)	The OCWD is responsible for managing the underground water reserves that supply about 500 wells within district boundaries. At the present time about 333 Mm^3 of this water is pumped for use each year. That quantity grows steadily, and projections indicate the demand may reach 555 Mm^3 a year in the next quarter-century.

Water Factory 21 and Groundwater Replenishment (GWR) System	Construction of the advanced wastewater treatment facility known as Water Factory 21 began in 1972, and injection of treated municipal wastewater began in 1976 via multiple cased injection wells. A series of 23 multi-point injection wells six kilometers (km) inland delivers freshwater into the underground aquifers to form a water mound, blocking further passage of seawater. Water Factory 21 originally received activated sludge secondary effluent from the adjacent Orange County Sanitation District Plant. The plant's treatment train included high lime chemical clarification, recarbonation, multimedia filtration, granular activated carbon, reverse osmosis (RO), chlorination, and blending. Extensive monitoring has verified that the product water contains no pathogenic bacteria, viruses, or parasites, and continually meets all drinking water standards. The new facility—the Groundwater Replenishment System—received approval in 2003 for expansion and upgrade of the reclaimed water production capacity for Water Factory 21, including expansion of its existing seawater barrier capacity. It will use the following multiple processes: microfiltration (treating 325,500 m^3/d), RO using thin-film composite membranes (treating 265,000 m^3/d), and UV light plus hydrogen peroxide treatment to produce 86.3 Mm^3/y of reclaimed water. The multi-barrier treatment approach also includes redundancy of barriers, groundwater filtration, and addressing emerging contaminants (e.g., N-nitrosodimethylamine [NDMA], 1,4-dioxane, endocrine disruptors, and pharmaceuticals). The water will either be recharged by surface spreading to augment water supplies or directly returned to the groundwater basin via injection wells to prevent saltwater intrusion from the Pacific Ocean. The Santa Ana River, which flows from the eastern Santa Ana Mountains to the Pacific Ocean, is the primary source of recharge water for the basin. The river water is composed of stormwater and wastewaters discharged from more than a dozen tertiary wastewater treatment plants. Along a six-mile (9.7 km) section of the Santa Ana River that belongs to the OCWD, a system of diversion structures and recharge basins captures most of the water that would otherwise flow into the Pacific Ocean. Water that flows down the Santa Ana River, together with supplies imported from the Colorado River and from the State Water Project, is channeled into nine recharge basins. These lakes and ponds have depths ranging from 15–46 m. The OCWD's facilities have a recharge capacity of approximately 370 Mm^3/y. It currently operates more than 405 ha of recharge facilities, and has 607 ha of land for use in its recharge program. About 50 percent of river flow is retained in 202 ha of wetlands, which provides nearly complete nutrient removal. About two million people depend on this source for more than three-quarters of their water.
West Basin Municipal Water District	After the prolonged California drought of 1987–1992, the West Basin Municipal Water District approved (in 1992) and constructed (completed in 1995) the Water Recycling Facility (WRF) located in El Segundo, CA. Using secondarily-treated wastewater from the City of Los Angeles Hyperion Wastewater Treatment Plant as a source, the original WRF included conventional filtration followed by disinfection to supply "disinfected tertiary recycled water" for a variety of uses in the West and Central Basin Municipal Water Districts service areas. Major industrial users include large oil refineries (Chevron and Exxon/Mobil), major commercial facilities (Toyota's South Campus office complex), and the Home Depot National Training Center (a major soccer and tennis facility). The plant also contained 19,000 m^3/d of conventional filtration (lime clarification and tri-media rapid sand filters) followed by disinfection and RO membrane treatment to supply water for injection in the West Coast Seawater Barrier. Barrier water is purchased from West Basin by the Water Replenishment District and injected in a 21-km-long series of deep injection wells owned and operated by Los Angeles County. Injecting recycled water into the West Coast Barrier constitutes an indirect potable reuse application via groundwater augmentation of the West Coast Groundwater Basin. Expanding the barrier water supply will also employ a UV/hydrogen peroxide advanced oxidation treatment process to achieve the highest levels possible of contaminant and pathogen removal.

Source: Adapted from various sources, including WPCF 1989; NRC 1994; SDLA 2003; and U.S. EPA 2004.

8. Water quality factors and proposed criteria for groundwater recharge

The following four water quality factors are significant in groundwater recharge with reclaimed water: (1) human pathogens, (2) mineral content, (3) heavy metals, and (4) trace organic compounds. Among them, human pathogens and trace organic compounds are of particular concern when groundwater recharge involves domestic water supply aquifers. There is considerable knowledge and experience with the removal or destruction of bacterial pathogens in wastewater. Much less is known about viruses, however, which are extremely difficult to isolate and detect. Some organic compounds are found in the most highly treated wastewater in milligram-per-liter quantities. These substances are often classified as stable organic compounds because they are resistant to treatment and cannot be readily decomposed or broken down. Some organic compounds are often classified as trace organic compounds because they have passed through extensive treatment processes. Stable/trace organic compounds are significant in groundwater recharge for the following reasons: (1) the identity of specific organic compounds is not well known, (2) it is unclear how treatment processes and passage through the soil affect stable organic compounds, and (3) the chronic health effects associated with ingestion of low levels of stable organic compounds over time are highly uncertain (State of California 1987). Recent discoveries of anthropogenic compounds such as NDMA and 1,4-dioxane in highly treated reclaimed water in the micro- or nanogram-per-liter concentration range have revealed that reclaimed water used for groundwater recharge projects can be vulnerable to pollutants of industrial origin that are not controlled at the source.

The State of California initially considered developing regulations to address groundwater recharge with reclaimed water in the mid-1970s. Since the late 1980s, California’s criteria for groundwater recharge (CGWR) have been under discussion and development through an interactive process with stakeholders. At present, proposed groundwater recharge projects are reviewed on a case-by-case basis using the proposed CGWR as guidance. While the current groundwater recharge regulations are only a “draft,” the requirements define—based on current knowledge—treatment and use area requirements that protect public health. Typically, the treatment technique or water quality characteristic requirements (either specific compound or surrogates concentrations) constrain project design to the domains of known performance for either specific compounds (controlled by concentration limits) or general classes of compounds (controlled by the application of treatment technology).

The proposed groundwater recharge criteria address both surface spreading and subsurface injection projects, and they are designed to ensure the local groundwater basin is not impaired or degraded by the groundwater recharge activities. The draft criteria address the primary topics of wastewater source control, wastewater treatment processes, water quality, dilution, recharge methods, operational controls, time underground, distance between the points of recharge and extraction of the groundwater, and monitoring wells. A summary of the proposed criteria and some of the salient features are excerpted in table 3.

Table 3. Proposed criteria for groundwater recharge with reclaimed water

Contaminant type in relation to treatment/control method	Surface spreading	Subsurface injection
Pathogenic microorganisms		
Filtration	≤ 2 NTU	
Disinfection	5-log virus inactivation,[a] ≤ 2.2 total coliform per 100 mL	
Retention time underground	6 months	9 months
Horizontal separation	150 m (500 feet)	610 m (2,000 feet)
Regulated contaminants	Meet all drinking water maximum contaminant levels (except nitrogen)	
Total nitrogen	3 mg/L	
Unregulated contaminants		
Filtration	TOC ≤ 16 mg/L [b]	
Reverse osmosis	If no mound monitoring, RO as needed to achieve: $TOC \le \frac{0.5 mg/L}{RWC}$ (in reclaimed water above ground at point of recharge)	100% RO treatment to $TOC \le \frac{0.5 mg/L}{RWC}$
	If mound monitoring, RO as needed to achieve: $TOC \le \frac{0.5 mg/L}{RWC}$ (in reclaimed water at mound monitoring compliance point)	
Mound monitoring option	Demonstrate feasibility of the mound compliance point	Currently not available
Recycled water contribution (RWC)	≤ 0.5 mg/L (Maximum RWC greater than 0.5 mg/L subject to the Department of Health Services approval)	

Source: Adapted from Hultquist et al. 1991; State of California 1992; and Crook et al. 2002.

[a] The virus log reduction requirement may be met by a combination of removal and inactivation.

[b] The TOC limit is intended to restrict recharge projects to effluents with the same TOC as those studied and used as a basis for these criteria. It is not intended as a performance standard for filtration.

9. Conclusions

With many communities approaching the limits of their available water supplies, water reclamation and reuse has become an attractive option for conserving and extending available water supplies. It is particularly attractive in the situation where the available water supply is already over-committed and cannot meet expanding water demands in a growing community. Groundwater recharge using reclaimed water is an approach that helps to make the water supply more sustainable. As technology continues to advance and the reliability and safety of water reuse systems is widely demonstrated, it is believed that water reuse via groundwater recharge will continue to expand as an essential element in sustainable water resources management.

References

Asano, T. ed. 1985. *Artificial recharge of groundwater*. Boston: Butterworth Publishers.

Asano, T., and K. L. Wassermann. 1980. Groundwater recharge operations in California. *Journal American Water Works Assoc*. 72 (7): 380–385.

Bouwer, H. 1978. *Groundwater hydrology*. New York: McGraw-Hill Book Co.

Crook, J., R. H. Hultquist, R. H. Sakaji, and M. P. Wehner. 2002. "Evolution and status of California's proposed criteria for groundwater recharge with reclaimed water." Proceedings of the American Water Works Association Annual Conference and Exposition, June 16–20, at New Orleans. Denver: American Water Works Association.

Hultquist, R. H., R. H. Sakaji, and T. Asano. 1991. "Proposed California regulations for groundwater recharge with reclaimed municipal wastewater." American Society of Civil Engineers Environmental Engineering Proceedings, 759–764, 1991 Specialty Conference/EE Div/ASCE, New York, NY.

Mantovani, P., T. Asano, A. Chang, and D. A. Okun. 2001. *Managing practices for nonpotable water reuse*. Project 97-IRM-6. , Alexandria, VA: Water Environment Research Foundation.

National Research Council (NRC). 1994. *Groundwater recharge using waters of impaired quality*. Washington, DC: National Academy Press.

Queensland Water Recycling Strategy. 2001. *Queensland water recycling strategy: An initiative of the Queensland Government*. Brisbane: Environmental Protection Agency, State of Queensland.

Sanitation Districts of Los Angeles County (SDLAC). 2003. *Fourteenth annual status report on reclaimed water use. Fiscal year 2002–03*. Whittier: SDLAC.

State of California. 1987. Report of the scientific advisory panel on groundwater recharge with reclaimed wastewater. Prepared for State Water Resources Control Board, Dept. of Water Resources, and Dept. of Health Services, Sacramento, CA.

———. 1992. Proposed guidelines for groundwater recharge with recycled municipal wastewater, and background information on proposed guidelines for groundwater recharge with recycled municipal wastewater. Sacramento, CA: Interagency Water Reclamation Coordinating Committee and the Groundwater Recharge Committee.

———. 2002. Statewide recycled water survey. Office of Water Recycling, State Water Resources Control Board, Sacramento,

CA, http://www.waterboards.ca.gov/recycling/docs/wr2002survey_attc.pdf

Todd, D. K. 1980. *Groundwater hydrology*. 2nd ed. New York: John Wiley and Sons.

U.S. Environmental Protection Agency (U.S. EPA). 2004. *Guidelines for water reuse.* EPA/625/R-04/108. Washington, DC: U.S. EPA.

Water Pollution Control Federation (WPCF). 1989. *Water reuse*. Manual of practice SM-3. Alexandria, VA: WPCF.

World Health Organization (WHO). 2003. *State of the art report: Health risks in aquifer recharge using reclaimed water*. SDE/WSH/03.08. Geneva: WHO.