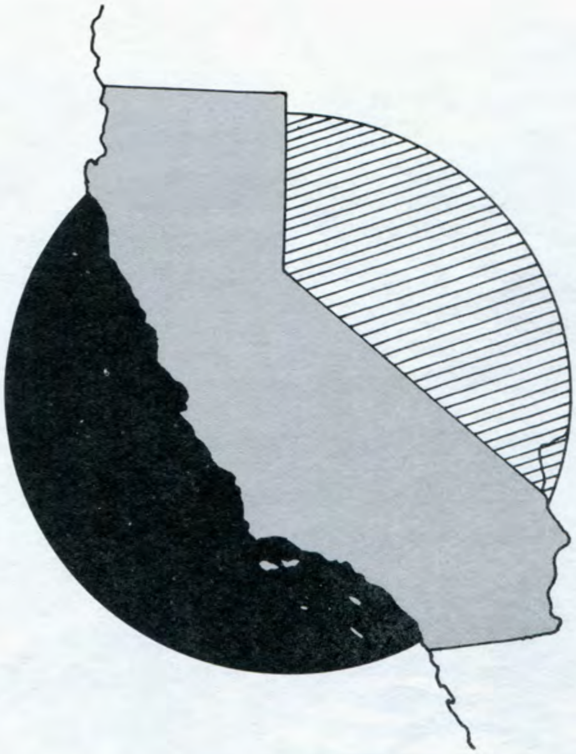

Groundwater Recharge Operations in California

Takashi Asano and Kurt L. Wassermann

The legislative directive contained in the California Water Code dictates that all possible steps be taken to encourage the development of water reclamation facilities to help meet the state's growing water requirements. Groundwater recharge with reclaimed municipal wastewater is an approach to water reuse that results in the planned augmentation of groundwater supplies.

The historical development of water resources in California has seen the transportation of water from the water-rich northern and eastern mountains to the Central Valley and the populated coastal regions of San Francisco, Los Angeles, and San Diego. The 1976–1977 drought of the western states focused attention on several water resource management options to meet the water needs of agriculture, industry, and urban areas. These options include measures to reduce water consumption, water exchanges and transfers, conjunctive use of ground and surface waters, and wastewater reclamation and reuse. While the drought highlighted the need for additional water resources development, it is anticipated that the next large increment of fresh water supply will be much higher in cost than existing supplies, due mainly to the remoteness of new water sources, energy and delivery costs, and environmental considerations.

As the demand for water increases, wastewater reclamation and reuse has become an increasingly important source for meeting some of this demand. In fact, the legislative directive contained in the California Water Code dictates that all possible steps be taken to encourage the development of water reclamation facilities to help meet the state's growing water requirements. Federal water pollution control regulations now require a minimum of secondary treatment and, in some cases, advanced treatment to meet effluent discharge standards, thus creating the unique opportunity for reuse with higher quality treated effluent. Consequently, discharging high quality effluent into estuaries and the Pacific Ocean is considered to be a waste of the state's limited water resources.

Groundwater recharge with reclaimed municipal wastewater is an approach to water reuse that results in the planned augmentation of groundwater supplies. Artificial recharge of groundwater with reclaimed water by surface spreading basins or with injection wells is becoming increasingly important in practice today and must be seriously considered in planning for increased water reuse in the future.

The purposes of artificial recharge of groundwater have been to reduce, stop, or even reverse declines of groundwater levels; to protect underground freshwater in coastal aquifers against saltwater intrusion from the ocean; and to store surface water, including flood or

The Los Angeles County Flood Control District's Rio Hondo spreading grounds, with a total area of 570 acres and a wetted area of approximately 455 acres, help control intrusion of seawater.

other surplus water, and treated effluent for future use. Groundwater recharge is also achieved incidentally in land treatment and disposal of municipal and industrial wastewater via infiltration–percolation.

There are several advantages in storing water underground.[1-3] The cost of recharge may be lower than the cost of equivalent surface reservoirs. The aquifer serves as an eventual distribution system and eliminates the need for surface pipelines or canals. Water stored in surface reservoirs is subject to evaporation and to pollution, which may be avoided by underground storage. Even more important, suitable sites for surface reservoirs may not be available or environmentally acceptable. However, before planned recharge of groundwater aquifers with reclaimed water can become a significant reuse application, several technical and health issues regarding wastewater treatment process reliability as well as the fate of pathogens, heavy metals, and inorganic and stable organic substances in the treated effluent and the aquifer must be carefully evaluated. Some basic questions needing to be addressed include

1. What treatment processes are available for producing water suitable for groundwater recharge?
2. How do these processes perform in practice?
3. How does water quality change during infiltration–percolation and in the groundwater zone?
4. What do infiltration–percolation and groundwater passage contribute to overall treatment system performance and reliability?
5. What are the important health issues?
6. How do these issues influence standards for water quality at the points of recharge and extraction?
7. What benefits and problems have been experienced in practice?

This paper describes locations and general conditions where significant groundwater recharge operations with reclaimed water have been practiced or are being planned in California, discusses the findings of the Consulting Panel on Health Aspects of Wastewater Reclamation for Groundwater Recharge,[4,5] and updates the groundwater recharge activities of the state Water Resources Control Board.

Groundwater Conditions and Recharge Potential

About 40 percent of the area of California is underlain by groundwater basins. The total storage capacity of the groundwater basins has been estimated to be 1.6×10^{12} m^3 (1.3 bil acre-ft) of water. A conservative estimate of the usable portion of the storage capacity is 176×10^9 m^3 (143 mil acre-ft), more than three times the total surface reservoir storage capacity in the state.[6,7] These groundwater basins presently provide about 40 percent [18×10^9 m^3/year (15 mil acre-ft/year)] of

California's applied water needs. However, the annual withdrawal exceeds recharge by about 2.7×10^9 m^3 (2.2 mil acre-ft). During the 1976–1977 drought of the western states, an estimated 10 000 new wells were constructed in California and groundwater overdraft increased to approximately 10×10^9 m^3/year (8 mil acre-ft/year).[8]

Without any action to improve water resources management and development of new supplies, statewide net demands in the year 2000 could exceed dependable supplies by as much as 8.1×10^9 m^3/year (6.6 mil acre-ft/year). To correct such unacceptable conditions, the Department of Water Resources developed a comprehensive water management program to meet projected water supply demands through the year 2000, as shown in Fig. 1. The plan combines several water resources management alternatives, including water conservation and alternative water supply development, and will reduce California's reliance on groundwater overdraft. Wastewater reclamation and reuse is expected to contribute a minimum of 740×10^6 m^3/year (600 000 acre-ft/year).

Since most of California's groundwater basins are in relatively arid valleys and most of the precipitation occurs at the higher elevations in the mountains, natural recharge of the groundwater basins occurs mainly by percolation from the streams flowing across the valleys. The amount of recharge has been increased in many areas by construction of shallow basins to broaden the area of permeable material covered by the water. As discussed previously, use of storage capacity of groundwater basins will benefit overlying groundwater users by decreasing pumping lifts and energy requirements, thus enhancing more comprehensive conjunctive use of ground and surface waters. Table 1 shows four hydrologic study areas where significant potential exists for management of ground and surface water supplies to help meet statewide water needs.

The extensive use of groundwater basins has caused several problems.[6] Pump lifts varying from 150 to 300 m (500 to 1000 ft) in some areas have made water too expensive for most agricultural uses. In several basins excessive pumping has produced saltwater intrusion from natural sources beneath or beside the basins. At times, disposal of wastes has added salts, disagreeable odors, or hazardous materials to the groundwater and impaired its usefulness. Extensive pumping of groundwater with reduction in pressure has caused deep-lying

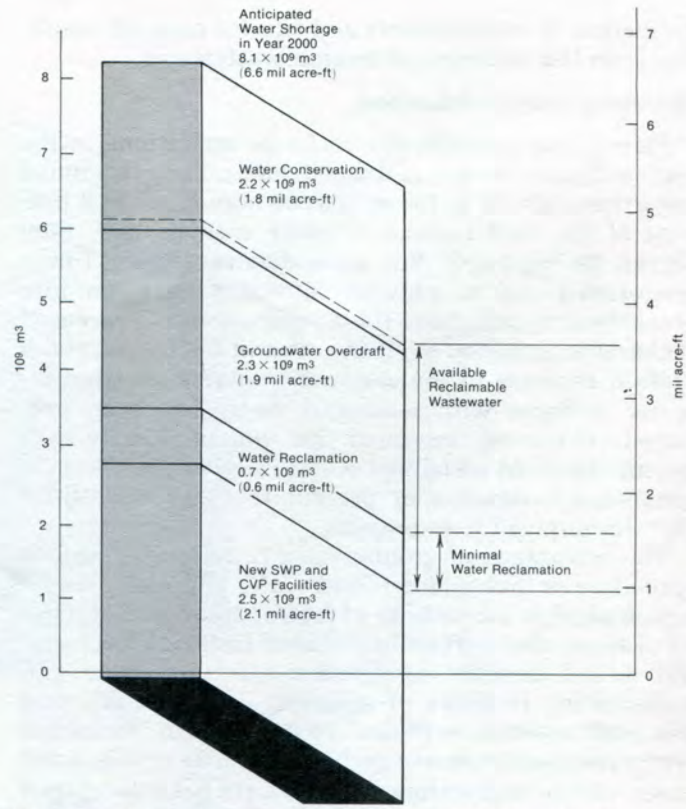

Fig. 1. Meeting Anticipated Water Shortage in California by the Year 2000 (After Robie[9])

TABLE 1

*Hydrologic Study Areas With Potential for Conjunctive Operation of Ground and Surface Waters**

Hydrologic Study Area	Number of Inventoried Basins and Sub-Basins	Area Covered		Estimated Storage Capacity		Yield and Basin Characteristics
		km^2	*sq mi*	$10^9 m^3$	*mil acre-ft*	
Sacramento Basin	24	16 600	6400	172	139.3	Usable storage capacity—27×10^9 m^3 (22 mil acre-ft); factors limiting development—low permeability, water quality, and well drilling and pumping costs; TDS—55-2790 mg/L; water type—$Ca(HCO_3)_2$, but $NaHCO_3$, $Mg(HCO_3)_2$ in certain areas; abundant and inexpensive water supplies, often filled to maximum storage capacity
San Joaquin Basin	9	35 500	13 700	94	80 (based on San Joaquin Valley)	Largest groundwater basin in California; usable storage capacity—>99×10^9 m^3 (>80 mil acre-ft); factors limiting development—water quality, pumping costs; TDS—64-10 000 mg/L; water type—east side of valley, $NaHCO_3$, $Ca(CO_3)_2$; west side of valley, Na_2SO_4. In 1973, 2×10^9 m^3 (1.6 mil acre-ft)[2] were artificially recharged or stored in San Joaquin Valley.
South Coastal Basin	42	8300	3200	13	10.4 (based on 29 basins)	Usable storage capacity difficult to estimate because of seawater intrusion, which is being artifically controlled in Los Angeles and Orange counties. The groundwater is generally suitable for all beneficial uses, but hardness is common. Almost all the basins are highly developed except in San Diego County.
Colorado Desert Basin	46	32 400	12 500	201	162.8 (based on 42 basins)	Usable storage capacity (7 basins)—12.7×10^9 m^3 (10.3 mil acre-ft); TDS—>600 mg/L, but highest recorded is 304 000 mg/L; water type—Na_2SO_4, NaCl; $Ca(HCO_3)_2$ in some places. Coachella Valley is one of the most highly developed groundwater basins.

*Source: *California's Groundwater*[6] and *The California Water Plan—Outlook in 1974*[7]

Fig. 2. Locations of Groundwater Basins With Areas of Overdraft and Seawater Intrusion (After *California's Groundwater*[6])

The San Gabriel River spreading grounds comprise 128 acres plus an additional 133 acres available in the river bed.

clay beds to compact, resulting in sinking of the ground surface.

Figure 2 shows the basins with groundwater overdraft and known areas of seawater intrusion.

Health Aspects of Water Reclamation for Groundwater Recharge

The planned augmentation of domestic water sources with reclaimed wastewater is being considered for several population centers in arid regions of the world. Within the state of California, there are five groundwater basin augmentation facilities. These groundwater recharge operations are summarized in Table 2. Water-short southern California is the area where groundwater recharge with reclaimed water has had its most extensive application, and it is also where major groundwater recharge projects are being planned. Future groundwater recharge projects in California have been identified that would introduce approximately 320×10^6 m^3/year (260 000 acre-ft/year) of reclaimed water into groundwater basins used for domestic water supply.[4]

Four water quality factors are of particular significance in situations involving groundwater recharge with reclaimed water: (1) microbiological quality, (2) total mineral content, (3) mineral toxicants of the heavy metal type, and (4) stable organic substances. Research programs are urgently needed so that the information for deciding under which conditions reclaimed water can be used for groundwater recharge will be available. Accordingly, the state of California has prepared a basic document[4] which has been used by the consulting panel to formulate research priorities in various areas, including research approach, sponsorship, recommendations, and implementation. The findings of the consulting panel were published in 1976.[5]

As noted, the panel was charged with recommending a program of research, including specific research and demonstration projects, that would provide information to aid state agencies in planning and implementing programs to encourage the use of reclaimed water consistent with these criteria.[5,11] Specifically, the panel was asked to

1. Define health problems and potential hazards related to the use of reclaimed water for groundwater recharge to augment domestic water supply
2. Identify the information needed before further decisions can be made about conditions under which reclaimed water can be used for groundwater recharge to augment domestic water supply
3. Identify the approach state agencies should take in developing information necessary to determine health effects and to establish reclamation criteria.

The panel recommended seven areas in which research is especially needed to resolve uncertainties concerning the health aspects of groundwater recharge:

1. Characterization of the contaminants in reclaimed water applied to the land, and in the water withdrawn from the ground for drinking
2. Study of water treatment processes for the removal of potentially harmful organics
3. Study of disinfection techniques and of viruses
4. Studies of the behavior of pollutants in soils and

sediments in underground environments

5. Assessment of toxicological risks

6. Epidemiological studies of exposed populations

7. Research and application of monitoring techniques and strategies.

With respect to objective 1, the panel has given its opinion on priority research dealing with development of information and techniques for characterizing reclaimed water used for groundwater recharge and detecting components in the underground environment. The panel feels that this effort should be initiated by studying existing projects entailing wastewater reclamation for groundwater recharge or by developing specific projects for this purpose.

On the related subject of health aspects of water reclamation for groundwater recharge, the current wastewater reclamation criteria[11] developed by the California Department of Health Services specify that

1. Reclaimed water used for groundwater recharge of domestic water supply aquifers by surface spreading shall be at all times of a quality that fully protects public health. The state Department of Health Services' recommendations to the regional water quality control boards for proposed groundwater recharge projects and for expansion of existing projects will be made on an individual case basis where the use of reclaimed water involves a potential risk to public health.

2. The state Department of Health Services' recommendations will be based on all relevant aspects of each project, including the treatment provided, effluent quality and quantity, spreading area operations, soil characteristics, hydrogeology, residence time, and distance to withdrawal.

3. The state Department of Health Services will hold a public hearing prior to making the final determination regarding the public health aspects of each groundwater recharge project. Final recommendations will be submitted to the regional water quality control board in an expeditious manner.

There is, however, no mention in the criteria of the direct injection of reclaimed water into domestic water supply aquifers. The Department of Health Services' positions regarding direct injections are understood to be that the department will in general recommend against direct injection of reclaimed water for groundwater replenishment, although direct injection for saline water repulsion and reclamation of saline aquifers is acceptable with proper controls.

Groundwater Recharge Research and Development Projects

Several groundwater recharge projects with reclaimed water have been implemented as a result of or have been influenced by the consulting panel's recommendations.

Health aspects of groundwater recharge in the Montebello forebay by the Los Angeles County Sanitation District. The objective of this \$1.4-million study is to assess the public health impact of the Montebello forebay groundwater recharge operation. Information generated by this project will include epidemiological assessment, determination of water quality changes occurring during recharge, and identification of wastewater components of public health concern. Montebello forebay is the largest groundwater recharge operation in the state, the combined capacity of the San Jose Creek and Whittier Narrow reclamation plants being approximately 26×10^6 m^3 (21 000 acre-ft).

Groundwater recharge with reclaimed water at Ely basin by Chino Basin Water District. The purpose of the demonstration program is to determine the effect on groundwater and soils of using reclaimed water for groundwater recharge by spreading. Identifiable organic and inorganic species will be monitored as they pass through the soil profile and into the groundwater. Particular emphasis will be given to trace organics monitoring. A further objective is to assess the effect of omitting chlorination prior to recharge and to compare the result with chlorinated extracted water.

Groundwater recharge by injection of reclaimed water in Palo Alto. The Santa Clara Valley Water District has constructed a treatment plant and wells to inject tertiary treated effluent into an aquifer in the Palo Alto bayfront area to serve as a barrier against seawater intrusion. As a long-term goal, this facility will be used for research to determine the feasibility of such a system for reclaiming water for potable uses. To answer questions related to the long-term effects of groundwater recharge (as recommended by the consulting panel), a three-year program has been undertaken by Stanford University. The purpose of the study is to acquire fundamental knowledge concerning the trans-

TABLE 2

*Major Groundwater Recharge Operations in California Using Reclaimed Water**

Wastewater Reclamation Plant	Treatment Processes†	Recharge Method	Type of Use	Annual Reclaimed Water Use	
				10^6 m^3	*acre-ft*
San Jose Creek	PS, AS, C, F, Ch	surface spreading	groundwater replenishment	17	13 447
Whittier Narrow	PS, AS, C, F, Ch	surface spreading	groundwater replenishment	9	7055
Water Factory 21	PS‡, AS‡, C, F, NS, CA, RO, Ch	direct injection	seawater intrusion barrier; groundwater replenishment	6	5115
Chino Basin	PS, TF	surface spreading	groundwater replenishment	0.3	258
Palo Alto	PS, AS, C, F, Ch, ozonation	direct injection	seawater intrusion barrier	0.2	184

*Source: *Wastewater Reclamation Facilities—Survey Report*[10]

†Treatment processes: AS—activated sludge; C—coagulation; CA—carbon absorption; Ch—chlorination; F—filtration; NS—ammonia stripping; PS—primary sedimentation; RO—reverse osmosis; TF—trickling filters

‡Treated at Orange County Sanitation District

formation of contaminants and aquifer material resulting from the injection of treated wastewater.

Summary and Conclusions

Five major groundwater recharge operations in the state of California use reclaimed water. They reclaimed approximately 32×10^6 m^3 (26 000 acre-ft) or 14.2 percent of the total reclaimed water used in 1977; they served to replenish the groundwater supply (three operations) and to prevent saltwater intrusion into groundwater aquifers (two operations). Increased recharge is expected at all five sites in the future, and a tenfold increase in the statewide volume for groundwater recharge with reclaimed water has been projected. However, concerns for potential long-term health effects of reclaimed water in groundwater have prevented expansion of present recharge operations and discouraged new projects.

The advantage of groundwater recharge by surface spreading is that underground water supplies may be replenished in the vicinity of metropolitan and agricultural areas where groundwater overdraft is severe, with the added benefits of filtering effect of soils and transporting facilities of aquifers. For economic and physical reasons, artificial recharge with reclaimed water requires intensive recharge over relatively small areas. Hence engineering methods have been developed to increase the rate of recharge through infiltration and percolation. Groundwater recharge by injection is practiced, in most cases, where the groundwater is deep or where the topography or existing land use such as urban areas makes basin recharge impractical or too expensive. This method of groundwater recharge is particularly effective in creating freshwater barriers in coastal aquifers against intrusion of saltwater from the sea. Because of the lack of additional treatment rendered by the soil systems, as in the case of surface spreading, an extensive aboveground treatment of wastewater must be provided.

Information recently developed by the Orange and Los Angeles counties regional water reuse study shows that some 62×10^6 m^3/year (50 000 acre-ft/year) of reclaimed water for saltwater intrusion barriers and 99×10^6 m^3/year (80 000 acre-ft/year) for spreading have been identified for the groundwater recharge in these basins. Although the volume of reclaimed water used for groundwater recharge is relatively small compared with California's water resources, significant benefits from groundwater recharge with reclaimed water are expected in the water-short coastal areas of Southern California.

The future potential of groundwater recharge with reclaimed water appears to center around questions other than engineering feasibility. Because of the very nature of the municipal wastewater used for groundwater recharge, significant public health and socioeconomic issues must be addressed and carefully evaluated before planned recharge of groundwater aquifers with reclaimed water can become a significant reuse application.

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