

ARTIFICIAL RECHARGE OF GROUNDWATER

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ABSTRACT

Since planning for droughts must be done in wet cycles, storing surplus surface water behind dams or in aquifers is essential. Underground storage is enhanced by increasing the infiltration of water into the soil, using in-channel and off-channel spreading systems and basins. In-channel spreading is achieved with low dams or weirs that increase the width and depth of streams, or by constructing T- or L-dikes in the streambed to spread the water over the entire width of the bed. Off-channel systems are mostly specially constructed infiltration basins or old gravel pits. Contrary to what may intuitively be expected, shallow basins tend to give higher infiltration rates than deep basins because there is less compaction of clogging layers that accumulate on the bottom due to suspended solids and biological activity. This is demonstrated with a soils engineering analysis and with field data. Artificial recharge can also be important in temporary storage of water, for example, in connection with seasonal changes in the use of sewage effluent for irrigation or in the demand for drinking water. For the latter, such aquifer storage and recovery generally is much less expensive than building water treatment plants with enough peaking capacity or surface storage. Artificial recharge also can play a role in the reuse of wastewater because it provides treatment benefits, gives seasonal storage, and improves the aesthetics of water reuse by breaking up the pipe-to-pipe connection of direct reuse.

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Introduction

Storage of water in times of water surplus is becoming increasingly important to meet water demands in times of water shortage. Water shortages occur where demands exceed supplies, where over-pumping of groundwater diminishes groundwater resources, and where there are extended dry periods. The possibility of reduced rainfall due to global climatic changes and greenhouse effects is prompting water agencies to look at different scenarios so that they will be prepared for the future. Natural recharge of groundwater is particularly vulnerable to changes in rainfall, especially in zones with low rainfall where a small reduction in precipitation can cause a large reduction in groundwater recharge.

All these factors focus attention on increased storage, surface as well as underground storage. The latter is achieved through enhanced recharge of groundwater (for example, by vegetation management to reduce evapotranspiration) and by artificial recharge with surface infiltration systems or through injection wells. Sources of water for artificial recharge include any surplus surface water and water of impaired quality such as sewage effluent, storm runoff, or irrigation return flow.

Infiltration Systems

Infiltration systems require permeable soils, vadose zones without severely restricting layers that could cause excessive perched mounding, and unconfined aquifers with sufficient transmissivity for lateral flow through the aquifer without excessive mounding (Figure 1). Also, soils, vadose zones, and aquifers should not be contaminated with undesirable chemicals, and there should be no other water quality problems. Conventional infiltration systems can be grouped into in-channel and off-channel systems (Figure 2).

In-channel systems are weirs, dams or levees that spread the water over a streambed or flood plain, usually designed to be replaced or repaired after spring runoff or other flooding. Dams may be built with washout sections, while the smaller weirs and levees are considered expendable and easy to reconstruct completely. Off-channel systems may consist of old gravel pits or of specially built basins. These are most common in California, where there are hundreds of successful projects. Infiltration rates during inundation often range from 1 to 10 ft/day. Year-round recharge systems with periodic drying and cleaning of the basins are typically rated at 100-1,000 ft/year. Periodic drying and cleaning are vital because soil clogging lowers infiltration rates. Silt, clay and other fines can accumulate to form clogging layers from less than 0.1 in. to more than 2 ft thick. Even with clear water, biofilms can develop on the wetted perimeter, and algae can clog the bottom soil.

logging tends to be more severe when the water is stagnant as in basins than when it is moving as in recharge channels or T-levee systems. When infiltration rates drop too low, drying the system shrinks and partially decomposes algae, biofilms and other organic deposits. This may be sufficient to restore infiltration rates. Clogging material such as silt or clay deposits must be physically removed from the bottom by "shaving" with a front-end loader, scraping or other means. Plowing or disking the clogging layers into the soil will improve the bottom temporarily, but the fines will then accumulate deeper in the soil so that eventually the entire top layer must be removed. Optimum lengths of flooding and drying periods depend on the soil, the suspended-solids content and nutrient levels of the water, and the climate. Some recharge systems in arid regions operate only during rain or flooding. Other cycles are controlled by environmental factors (insect breeding, odors, slightly floating algae) or recreational demands. Thus, cycles may vary from four days flooding and 10 days drying to 11 months flooding and one month drying.

The water depth in infiltration basins should be carefully selected. The hydraulic heads of large water depths produce high infiltration rates, but they also tend to compress clogging layers, raising the hydraulic resistance of the bottom. Thus, contrary to intuitive expectations, deep basins can produce lower infiltration rates than shallow basins (Bouwer and Rice, 1989). Also, the rate of turnover of the water in a deep basin may be less than in a shallow basin, allowing more suspended algae to grow in longer exposure to sunlight. This aggravates the clogging by formation of an algal filter cake on the bottom, and by precipitation of calcium carbonate due to increases in the pH of the water resulting from uptake of dissolved carbon dioxide by photosynthesizing algae.

The second design criterion is that the ground-water table must be deep enough below the infiltration system so that it does not interfere with the infiltration process. This applies to the permanent water table and the mounding caused by recharging, as well as to perched ground-water mounds that may form on restricting layers in the vadose zone. Where infiltration rates are controlled by the clogging layer (which is the rule rather than the exception for basins and ponds), the water table must be 3 ft or more below the bottom of the basin. Where there is no clogging layer, the vertical distance of the groundwater table below the water surface of the infiltration system at some distance from the ponds should be at least twice the width of the infiltration system if infiltration rates are not to be encumbered by groundwater levels. Thus where groundwater levels are high, maximum

infiltration rates can then only be obtained with long narrow streams or basins spaced well apart. Equations have been developed to calculate the rise of groundwater mounds below infiltration systems (Bouwer, 1978, and references therein).

Infiltration systems must be tailored to local geohydrology, water quality and climate. In general, basins should be less than 2 ft deep and hydraulically independent so that each can be flooded, dried and cleaned according to its best schedule. Inlet structures must not cause soil erosion that could clog basin bottoms. Drying periods should be started before infiltration rates have reached low values. Drying is then accomplished by infiltration, and pumping or draining the basins is not necessary. Finally, there should be a number of basins for flexible operation, with some in reserve to handle maximum water flows.

Water Quality

For relative pure water, the most important quality parameters for groundwater recharge are suspended solids (SS), total dissolved solids (TDS) and major cations such as calcium, magnesium and sodium. Periodic cleaning is necessary when SS causes clogging of the wetted perimeter of infiltration systems. Where the SS content is too high, the water is first passed through desilting or presedimentation basins to reduce cleaning costs. Coagulants may be added for this process, and on-site experiments will determine the best combination of pretreatment and cleaning schedules for hydraulic capacity and economy of operation. TDS and concentrations of calcium, magnesium and sodium determine whether a clay is dispersed or flocculated and therefore whether it has a relatively low or high hydraulic conductivity. This affects clay in the clogging layer and further down. Thus, TDS, calcium and magnesium should be high enough and sodium low enough to keep clay in the clogging layer and below in a flocculated, relatively permeable state.

In infiltration systems, recharging sewage effluent, storm runoff or other polluted water can improve its quality. Suspended solids are removed, biodegradable organic matter is decomposed, microorganisms are taken out, concentrations of nitrate and synthetic organic compounds are reduced, and phosphate and heavy metals are immobilized. Because of this, groundwater recharge can be used as a step in the treatment train for reuse of wastewater. It is then called soil-aquifer treatment (SAT) or geopurification (Bouwer, 1991).

To protect high-quality native groundwater and nearby drinking water wells, SAT systems are designed as recharge-recovery systems where recharge water is pumped out of the aquifer again with strategically located interceptors. The

water typically can be used as such for irrigation and recreation and, with further treatment, for drinking. SAT systems are inexpensive and simple to operate, and enhance the aesthetics of using recycled sewage for public water supplies by breaking the toilet-to-kitchen faucet connection. Special regulations are being developed in California for blending of recharge water with native groundwater to allow potable use of the water after SAT without further treatment (Hultquist et al., 1991).

Well Injection Systems

Groundwater recharge with infiltration systems is not feasible where permeable surface soils are not available, vadose zones have restricting layers or are otherwise unsuitable, or aquifers have poor quality water at the top or are confined. For those conditions, groundwater recharge can be achieved with injection wells. To prevent clogging of the aquifer interface around the recharge well, the water should first be treated to remove all suspended solids. To minimize growths of biofilms, BOD, nutrients, and microorganisms should also be removed. Even then, a residual chlorine content still is necessary to control bio-clogging of the well and aquifer. Thus, water for well injection should be treated to essentially drinking water standards before it goes into the well. In addition, the wells should be frequently pumped (about 10 minutes per day, for example) and periodically redeveloped, depending on decreases in specific capacity for recharge. This makes groundwater recharge through wells much more expensive than recharge with infiltration basins. Where reclaimed sewage effluent is used for well injection, treatment benefits in the aquifer tend to be relatively small because aquifers usually are coarse textured. However, SAT systems with well injection still offer the benefits of aesthetics and improved public acceptance of water reuse (no pipe-to-pipe connection), and some quality improvement ("aging" and "polishing" effects).

Aquifer Storage and Recovery (ASR) Wells

A new and rapidly spreading practice in artificial recharge is the ASR well. These wells are combination recharge and pumping wells. They are used for recharge when surplus water is available, and pumped when the water is needed. ASR wells typically are used for seasonal storage of drinking water in areas where water demands are much greater in summer than in winter. Drinking water treatment plants then are designed for mean annual capacity. The winter surplus is stored underground with ASR wells, which are pumped in the summer to augment the production from the water treatment plant. The only treatment for the water from the wells then is chlorination. The combination of mean flow capacity treatment plants and ASR wells is cheaper than peak flow capacity treatment plants and no wells.

Artificial Recharge Issues

Currently, there are three main issues in artificial recharge of groundwater: health effects, system sustainability, and artificial recharge under difficult soil and hydrogeological conditions. Concern about health effects occurs primarily in recharge systems where the source water is of low quality; i.e., sewage effluent, storm runoff, or agricultural runoff or return flow. The main concerns are about toxic organic compounds ("bad TOC!") that have survived the SAT process, and about disinfection byproducts (DBPs) if the water after SAT is chlorinated (other disinfection processes may also produce DBPs). DBPs can also be present in the water before SAT, if sewage effluent is chlorinated before discharge and the DBPs are not removed by SAT. For these reasons, it may be best to only mildly chlorinate or otherwise disinfect the effluent prior to infiltration, and then use UV after SAT when the turbidity of the water is very low for final disinfection. Humic and fulvic acids may be formed in the soil during SAT. These compounds are known THM-precursors. Thus, the water after SAT preferably should not be chlorinated but disinfected with other techniques such as UV.

In general, adverse health affects from drinking water after SAT or low quality input water can best be minimized by designing SAT systems with complete, systematic recovery of the recharge water from the aquifer. This then allows post-treatment of water after SAT with the appropriate technology (activated carbon filtration, reverse osmosis, UV irradiation) to minimize bad TOC and DBPs in the water. Where the recovery of water after SAT is with randomly distributed wells in the aquifer system, post treatment is difficult and dilution with unpolluted native groundwater is relied upon to get bad TOC and other toxic materials to low concentrations. For example, new California regulations would allow only 20 to 50% sewage derived water in the well water, depending on the treatment of the sewage prior to infiltration (Hultquist et al., 1991).

Health effects are extremely difficult to assess. Epidemiological studies of the population drinking the water are extremely expensive and often inconclusive. Toxicological studies, including rodent bioassays on concentrates of the water after SAT, also may not be meaningful. Other health concerns are primarily microbiological and have to do with pathogens that may be ingested by eating raw vegetables irrigated with sewage water after SAT, inhaling aerosols, and accidental ingestion where water after SAT is used for swimming. There is also concern about contact with the water as with parks and playgrounds irrigated with the water, or farmers using the water for irrigation.

Sustainability of SAT systems has to do with the possible accumulation of certain minerals and organic compounds in the soil and aquifer and how this

ffects the underground environment. Most SAT processes are renewable and stainable (removal of BOD, NO_3 , turbidity, and microorganisms). However, some chemicals may go through SAT (refractory organics), and some may accumulate in the soil and aquifer (adsorbed organics, metals, phosphate). Little is known about accumulating effects, although SAT systems generally are considered as having very long useful lives (decades, centuries). More knowledge on the sustainability of SAT and the proper closing and commissioning of SAT projects is needed.

Because artificial recharge and SAT offer distinct advantages over other options (surface storage, in-plant treatment), interest is growing in doing artificial recharge and SAT under unfavorable conditions, such as less permeable soils, shallow bedrock, or restricting layers in the vadose zone. For such conditions, protocols for step-by-step site investigation procedures must be set up to evaluate the conditions and to make sure that there are no "fatal flaws" that make recharge and SAT essentially impossible. The costs of these investigations may be high, but the costs of an undetected fatal flaw may be much higher. SAT will be more expensive per acre foot of water for less favorable than for favorable conditions, but it may still be cheaper and more advantageous than other options.

Conclusions

Artificial recharge with infiltration systems is an effective way for storing water underground and for improving the quality of the water, especially if it is sewage effluent or other water of low quality. Where surface infiltration is not feasible or possible, aquifers can be recharged through injection wells. This process, however, requires pretreatment of the water to essentially drinking water standards, and is much more expensive (often an order of magnitude more) than recharge with surface infiltration systems. Artificial recharge is an important tool in water resources management, storing surplus water during times of adequate supplies for use in times of water scarcity. Artificial recharge with full recovery of the water from the aquifer also will be an important tool for water reuse because it provides low cost treatment and storage of the water, and it enhances the aesthetics and public acceptance of water reuse by breaking up the pipe-to-pipe connection of direct reuse of wastewater.

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