DESIGN AND MANAGEMENT OF INFILTRATION BASINS FOR ARTIFICIAL RECHARGE OF GROUND WATER [1]

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INTRODUCTION

With artificial recharge of ground water, surface water is infiltrated into the ground for storage in aquifers and eventual recovery from wells. Infiltration and flow to aquifers can be achieved with infiltration facilities on the surface (see Figure 1). Such systems require permeable surface soils to obtain adequate infiltration rates, vadose zones without clay or other flow-restricting layers that would inhibit the flow to the aquifer, and aquifers that are unconfined. Where these conditions do not exist, or where suitable land would be too expensive, artificial recharge of ground water can be achieved with wells.

Recharge Wells

Recharge or "injection" wells are similar in construction to pumped wells, using screened section(s), gravel packs (in unconsolidated aquifers), and grouting. Before injection, the water needs to be carefully treated to remove essentially all suspended materials. Even then, injection wells in unconsolidated aquifers eventually clog up at the interface between the well and aquifer. This requires periodic pumping and/or redevelopment (surging, jetting) of the well. Because of clogging, the specific capacity of wells for injection into unconsolidated aquifers is only about half the specific capacity for pumping. Injection wells in fractured-rock aquifers or in limestone with solution channels or other well-developed secondary porosity have injection rates that are closer to pumping rates. Water for injection wells should be applied through a relatively small pipe in the well that ends below the water level. This is to avoid free fall of the water in the well and resulting entrainment of air in the water. Dissolved air in the recharge water could cause problems of "air binding" in the aquifer as air goes out of solution and forms entrapped air in the aquifer if the recharge water is colder than the ground water. The entrapped air can significantly reduce the hydraulic conductivity of the aquifer around the well and, hence, the injection rate. Ground water recharge with injection wells usually is much more expensive than recharge with spreading or infiltration basins, often by an order of

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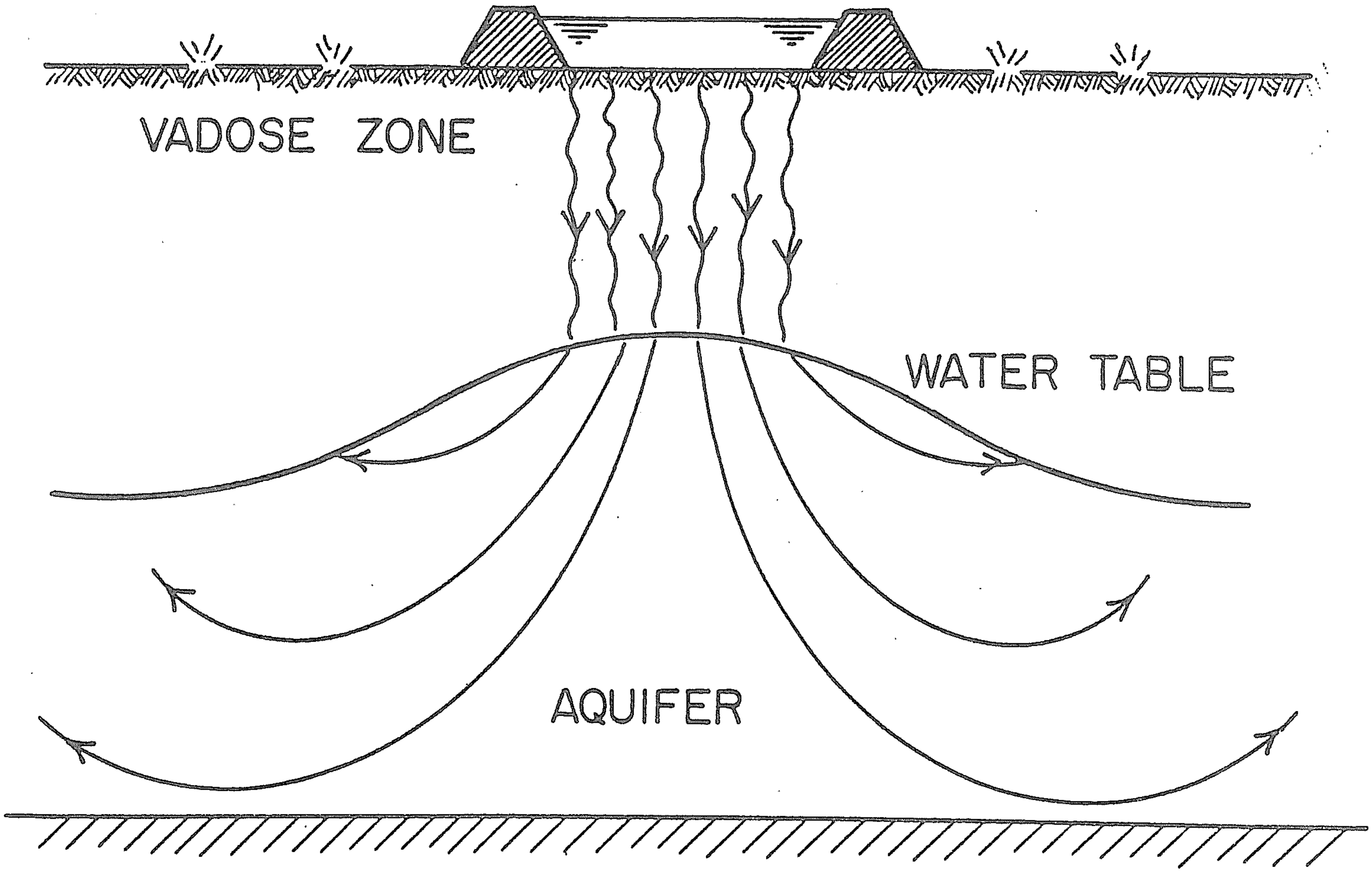

Figure 1. Schematic of ground water recharge system showing infiltration basin, vadose zone with wetted zone (wiggly lines), ground water mound, and flow lines in aquifer.

magnitude. Therefore, the rest of this paper will be devoted to design and management of infiltration systems for ground water recharge.

Infiltration Systems

Infiltration facilities for ground water recharge can be divided into in-channel and off-channel systems. In-channel systems consist of weirs, dams, and levees (T-dikes or L-dikes) to increase the wetted area and, hence, the infiltration in the stream bed or floodplain. Off-channel systems are basins in old gravel pits or specially constructed basins in areas of permeable soil. Design and management criteria to maximize the hydraulic capacity of infiltration basins depend on water quality, climate, and soil. Thus, these criteria are site-specific and they must often be evaluated by on-site experimentation. Factors to be studied are optimum schedules of flooding, drying, and cleaning of the basins; optimum pre-treatment of the water; optimum water depth; and optimum velocity of the water (basins with stagnant water versus channels with flowing water). There are also environmental factors to be considered (insects, algae, odors). Sources of water for artificial recharge of ground water include surplus water in streams and rivers (including possibly increased flow due to cloud seeding or water harvesting techniques), storm water runoff, surplus water in aqueducts or water transfer projects (California Aqueduct, Central Arizona Project), and sewage effluent or other wastewater. Some water sources are continuous and permit year-around operation of the infiltration basins. Others are seasonal or haphazard.

Basin Management

Infiltration rates in flooded basins decrease with time due to accumulation on the bottom of sediment that was suspended in the water. Biological activity in the water (growth of algal cells that form a filter cake on the bottom upon infiltration), and on the bottom (bacterial and algal activity) can also reduce infiltration through formation of clogging layers. Thus, the basins must be regularly dried and cleaned to restore infiltration rates. If the clogging material consists primarily of silt, clay, or other inorganic matter, it must be removed by scraping, raking, or other procedure that removes only the clogging material. Disking the clogging material into the subsoil gives temporary improvement, but ultimately the entire soil layer to the depth of disking may have to be removed because of accumulation of fine particles. If the clogging material is primarily organic (sludge, bacteria, algae), drying alone can give considerable recovery of infiltration rates due to the decomposition, shrinking, cracking, and curling-up of the material. Under those conditions, cleaning the basin bottoms may not be necessary for every drying period, but may be done only occasionally, like once or twice a year. The best combination of drying and cleaning schedules must be determined on-site, especially for projects in new areas where there is no local experience with management of infiltration basins.

Sometimes, flooding and drying cycles are controlled by life-cycles of insects. To avoid nuisance problems, flooding periods may have to be only a few days to prevent hatching of insect eggs and emergence of adult insects (for example, the midge flies in California).

Where the water for recharge basins contains considerable suspended material, it can be more economical to remove this material in pre-sedimentation basins with possible use of coagulants to enhance settling of the solids. However, this costs money. On the other hand, not removing suspended solids first and letting them all accumulate on the bottom of the infiltration basin costs money, too, in the form of frequent drying and cleaning of the basins. Thus, there is an optimum combination of pre-treatment and drying and cleaning of the basins. This economic optimum must be determined for each individual system where pre-sedimentation appears desirable.

Where surface water is available for artificial recharge of ground water during most of the year or the entire year, there may be an interest in using the infiltration basins also for recreational purposes. Such use places constraints on the management of the basins for maximum hydraulic loading. Regular drying and cleaning may then be more difficult. Pre-sedimentation may be desirable to minimize sediment accumulation on the bottoms of such basins.

A choice can be made between infiltration basins that have essentially stagnant water where even the finest suspended material can settle out, and infiltration channels where the water is kept moving to create enough turbulence to keep the fine material in suspension. On-site testing needs to be done to see which system is better and gives the highest infiltration rates. If the channel system with moving water is used, a few infiltration basins may have to be constructed at the end of the channels to catch any residual flow.

Effect of Water Depth

Intuitively, one would think that a large water depth in infiltration basins gives higher infiltration rates than a small water depth. This may not always be so, however. If the ground water table is above the bottom of the basin, as can happen if the basins are in old gravel pits or where ground water tables are high, then an increase in water depth could produce a significant increase in infiltration rate. If the ground water table is a considerable distance below the bottom of the basin, an increase in water depth will produce only a small increase in infiltration rate if the basin bottom and banks are clean (not covered by sediment or other clogging material). This can be demonstrated by applying Darcy's equation to the flow from the basin to the ground water. If, however, the wetted perimeter of the basin is covered by a well-developed clogging layer (organic or inorganic), the entire head due to water depth in the basin is dissipated across the clogging layer, and the infiltrated water moves as unsaturated flow to the underlying ground water. Applying Darcy's equation to the flow through the clogging layer then shows that for this case there is an almost linear relation between water depth in the basin and infiltration rates. In that case, for example, doubling the water depth would essentially double the infiltration rate. However, there are other effects that can negate this linear relation.

The first effect is compaction of the clogging layer due to an increase in the seepage force across this layer as the water depth and, consequently, the head loss across the clogging layer, are increased (see Figure 2). The compaction of the clogging layer produces a significant decrease in the hydraulic conductivity of this layer, causing a lower increase in infiltration rate than expected from the hydraulic head (water depth) increase alone, and perhaps even a decrease, depending on the type of clogging material.

The second effect is that if increasing the water depth does not produce a proportional increase in infiltration rate, the turnover rate of the water in the basin decreases, which could promote the growth of suspended, unicellular algae in the water due to longer exposure to sunlight. The algae will then be filtered out on the bottom as water infiltrates and form a filter cake on the clogging layer, which further reduces the hydraulic conductivity of this layer and, hence, the infiltration rate. This, in turn, reduces the turnover rate in the basin even more, increasing the exposure of suspended algae to sunlight which increases the growth of algae and further clogs the bottom layer with the algal filter cake, and so on.

The third effect is that at high algae concentrations, uptake of carbon dioxide from the water for photosynthesis by the algae becomes significant, causing the pH of the water in the basins to increase to values as high as 9 or 10. At these pH values, calcium carbonate will precipitate out and accumulate on the bottom, further aggravating the clogging process and reducing infiltration rates even more.

In view of these processes, shallow basins may actually produce higher infiltration rates than deep basins where the wetted perimeter of the basin is covered with a clogging layer. Since a number of factors govern the relation between water depth and infiltration rate, the water depth giving maximum infiltration rates must be evaluated by on-site experimentation. If deep basins are considered or changeovers from shallow basins to

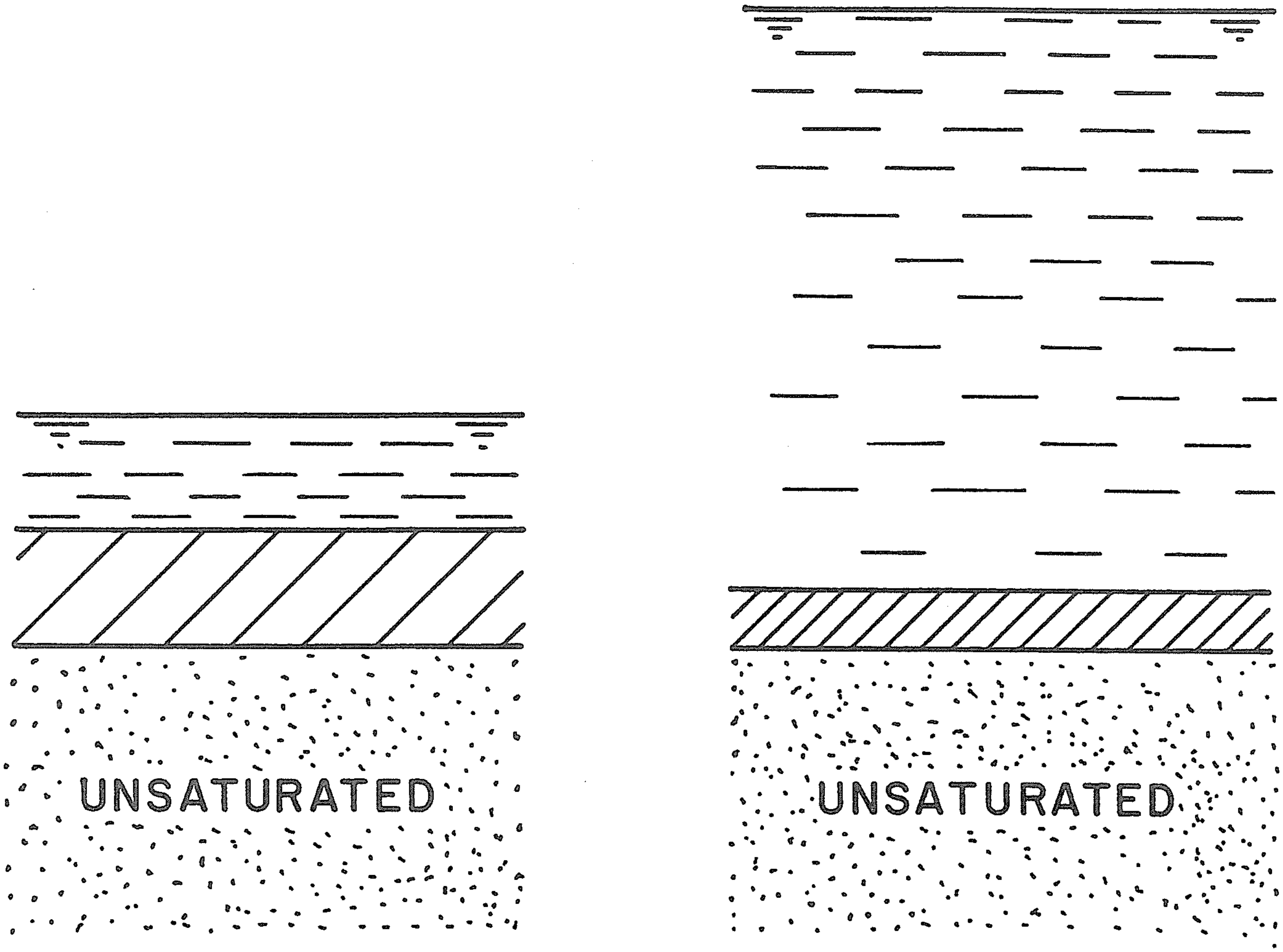

Figure 2. Compaction of clogging layer (hatched) by increasing water depth from small (left) to large (right).

deep basins are contemplated, the local conditions should be thoroughly investigated, and studies with test basins should be made to ensure that the deep basins will produce the desired results.

Site Selection and Hydraulic Loading Rates

Since infiltration basins for artificial recharge of ground water require permeable soils, identification of permeable soil profiles and site selection are extremely important. Small cylinder infiltrometers, double-ring (buffered) as well as single-ring systems, are useful for comparisons and measuring relative infiltration rates, but they overestimate the infiltration rates for larger inundations and cannot be used to predict hydraulic loading rates for infiltration basins (Bouwer, 1986). Such prediction is better achieved with larger test basins and by supplementing infiltration tests with measurements of soil hydraulic conductivity in the vadose zone. For unclogged basins and deep ground water tables, basin infiltration rates are approximately equal to the average resaturated hydraulic conductivity (harmonic mean, see Bouwer, 1978, pp. 56-60 and pp. 253-254) of the vadose zone or upper portion thereof. Thus, hydraulic conductivity measurements can give a good estimate of maximum hydraulic loading rates attainable with the basins.

Methods available for in situ measurement of resaturated hydraulic conductivity in the vadose zone include the air-entry permeameter, double-tube method, infiltration gradient technique, and reverse auger hole or well pump-in method (Bouwer, 1978, p. 123-130). Hydraulic conductivity of stony or gravelly materials can be estimated from the hydraulic conductivity of the soil between the gravel or boulders and the volume fraction of the rock or void ratios of the soil and rock matrix (Bouwer and Rice, 1984a).

Permeable soils typically have hydraulic conductivities in the range of 3 ft/day (fine loamy sands) to 30 ft/day and sometimes even higher (sands, and sand and gravel mixes). Because of clogging, infiltration rates of recharge basins tend to be less than the resaturated hydraulic conductivity of the underlying soil materials. Actual infiltration rates during flooding thus generally vary from about 1 ft/day to 10 ft/day. For year-around operations and including time for drying and cleaning the infiltration basins, hydraulic loading rates or accumulated infiltrations typically range from 100 to 1000 ft/yr.

Ground Water Mounds

When the infiltrated water joins the underlying unconfined aquifer, a ground water mound is formed (see Figure 1), and the recharge water moves mostly laterally through the aquifer to produce smaller ground water table rises further away. The rise of ground water mound during infiltration and the fall of the ground water mound during drying can be predicted with Hantush's equation (Bouwer, 1978, p. 283). This equation can also be used to calculate the effect of the infiltration system on ground water levels at various distances from the infiltration basins. If there are complicating factors in the aquifer system, such as a natural ground water table slope and other recharge or discharge mechanisms (losing streams, wells, springs, uptake of ground water by vegetation, etc.), the effect of artificial recharge on ground water levels can be estimated by modeling the aquifer system, using finite difference or finite element analysis techniques.

Aquifers should be sufficiently transmissive to keep ground water mounds below the bottom of infiltration basins if reductions in infiltration rates are to be avoided. A long, narrow infiltration basin or system of basins produces lower ground water mounds than square or round systems with the same area and hydraulic loading.

Water Quality

As the infiltrated water moves through the vadose zone and aquifer, some quality parameters may be improved, and some may be adversely affected. Constituents that are partly or almost completely removed from the water as it moves through the vadose zone and aquifer include suspended solids, bacteria, viruses, other microorganisms, biodegradable material (BOD), nitrate, and some synthetic organic compounds (particularly the non-halogenated hydrocarbons). Since the soils in ground water recharge systems normally are quite coarse and permeable, there is little or no clay, and ion exchange will be insignificant. Hence, the ionic composition of the water after it has moved through the vadose zone and aquifer generally will be about the same as that of the water entering the infiltration basins.

Adverse effects include mobilization of iron and manganese from the vadose zone and aquifer as oxygen levels are reduced, and leaching of trace elements (including selenium, arsenic, boron, cadmium, molybdenum, and mercury) from the vadose zone. Leaching of trace elements may be significant where soils are relatively fine and almost marginal for artificial recharge of ground water, and where the soils have not had a long history of infiltration. Such soils include basin and valley soils and marine deposits, i.e., the San Joaquin Valley in California where selenium is leached from the soil and appears in the drainage water from the irrigated fields. Alluvial fans, stream channels, and floodplains generally would not be expected to have problems of leaching of trace elements, but it should be checked to avoid unpleasant surprises later on.

There may also be concern for humic and fulvic acids and algal compounds and metabolites that may already be in the water before infiltration. These organics may not be completely removed in the vadose zone and aquifer. Since they react with chlorine to form trihalomethanes (THMs), special consideration may be required when the water is pumped from the aquifer and needs to be disinfected for drinking (Fam and Shenstrom, 1987). However, unpolluted, pristine ground water also contains organic carbon, mostly as fulvic or humic acids and typically at concentrations of about 0.2 to 0.7 mg/l (Thurman, 1979). Such water is commonly disinfected with chlorine when used for public water supplies, without giving much thought to the possibility of forming THMs.

From an operational standpoint, the most important quality parameters of the water going into infiltration basins are the total dissolved solids content (TDS) and the sodium adsorption ratio (SAR), calculated as $Na/[(Ca+Mg)/2]^{1/2}$ with the concentrations expressed in meq/l. TDS and SAR control whether clay in the soil is flocculated or dispersed. A flocculated state is preferred because a soil with such a clay is much more permeable than a soil with dispersed clay. A low SAR and a high TDS favor flocculation, whereas a high SAR and a low TDS favor dispersion of clay (see McNeal's graph in Bouwer, 1978, p. 44). Soils below infiltration basins generally are sandy or gravelly and contain little or no clay. The same is true for aquifers. Thus, SAR and TDS will have little or no effect on the hydraulic conductivity of vadose zones and aquifers, but they will have an effect on the hydraulic conductivity of the sediment layers on the basin bottoms. Such layers consist of fine materials and often contain clay that was suspended in the water. Clogging due to inorganic sediment accumulations on the basin wetted perimeter thus tends to be more severe where SAR and TDS cause the clay to be dispersed than where the clay is flocculated, necessitating more frequent cleaning operations for the former. Sometimes, dispersing SAR and TDS values can mobilize clay particles in the aquifer system. These particles can then migrate through the aquifer and move to wells where they increase the turbidity of the pumped water.

Recharge with Sewage Effluent

Where sewage effluent is used for ground water recharge, the quality improvement of the sewage water as it moves through the vadose zone and aquifer becomes very significant. As a matter of fact, this "treatment" aspect may be the most important part of the recharge system, and the main purpose of the recharge system could be to give "soil-aquifer treatment" (SAT) to the effluent. SAT systems typically are designed and managed as recharge-recovery systems. The product water or "renovated" sewage water from SAT systems can be used for stream flow replenishment, unrestricted irrigation (including crops consumed raw by humans), and drinking (after further treatment and/or blending with other water).

Sewage effluent typically has had primary and secondary treatment and mild chlorination before it is used for ground water recharge. Primary effluent can also be used as such, but infiltration rates tend to be less due to more suspended solids and clogging. Thus, where primary effluent is used, a larger area will be necessary for the infiltration basins. As the effluent moves through the vadose zone and aquifer, the following quality improvements can be expected, as indicated by a pilot project (Bouwer et al., 1980) and a demonstration project (Bouwer and Rice, 1984b) in the Phoenix, Arizona, area.

1. Suspended solids, biodegradable material (expressed as biochemical oxygen demand or BOD), bacteria and viruses are essentially completely removed.
2. Concentrations of phosphorus and heavy metals are greatly reduced (phosphate by about 90 percent to about 0.5 mg/l as phosphate phosphorus).
3. When the flooding and drying periods of the basins are selected to stimulate denitrification in the soil (obtained in the Phoenix area with flooding and drying periods of about 10 days each), nitrogen concentrations are reduced by about two-thirds. For the Phoenix project, this left about 6 mg/l of nitrogen in the renovated water, almost entirely in the nitrate form.
4. Total organic carbon content is reduced to about 2 mg/l. Most of this carbon probably is in the form of humic and fulvic acids, but there is also a wide spectrum of refractory synthetic organic compounds, mostly at concentrations on the ppb (micrograms/l) level. Halogenated hydrocarbons were more persistent than non-halogenated hydrocarbons in the underground environment.
5. The TDS content of the renovated water was about 2 percent higher than that of the sewage effluent, mostly due to evaporation from the basins.

The renovated water from the Phoenix project meets the public health, agronomic, and aesthetic water quality requirements for unrestricted irrigation and recreation. If the renovated water is to be used for drinking, further treatment is required. This treatment could consist of activated carbon filtration to remove TOC, disinfection, and possibly reverse osmosis. Because considerable quality improvement has been obtained by the flow through the vadose zone and aquifer, treatment of renovated water from an SAT system for drinking will be much more effective and economical than treatment to convert sewage plant effluent directly into drinking water.

The Phoenix projects are in loamy sand overlying coarse sand and gravel. Hydraulic loading rates are about 300 ft/yr. Thus, one acre of infiltration basin can handle 300 acre-feet of sewage effluent per year or 0.37 mgd. Evaporation rates are about 6 ft/yr.

Thus, the recovery efficiency is about 98 percent. The ground water table is at a depth of about 10 feet in the pilot project and 50 feet in the demonstration project.

After the recharge water has moved through the vadose zone and some distance through the aquifer, its quality often is still not as good as that of the native ground water. Thus, SAT systems should be designed and managed for complete recovery of the renovated sewage water within a given distance (a few hundred to a few thousand feet, for example) from the infiltration system. This not only assures complete recovery of the infiltrated sewage water, but it also protects native ground water resources outside the aquifer portion dedicated to SAT.

Examples of various types of SAT systems with complete recovery of renovated water are shown in Figure 3. The top system, where renovated water drains into surface water, is used to reduce pollution of surface water by wastewater. Cities or towns using this system may get credit for the return flow into the stream and be allowed to divert more water from the stream. If they discharge their sewage effluent directly into the stream, they would not get credit and would require a discharge permit. The system in Figure 3B can be used where ground water tables are high and the renovated water can be recovered by gravity with underground drains. Where the ground water is deep, the renovated water must be recovered with wells. For Figure 3C, encroachment of renovated water into the aquifer outside the SAT system is prevented by monitoring ground water levels at the outside of the system (see observation wells in Figure 3C), and managing infiltration and well pumping rates so that ground water levels at the observation wells never rise higher than the ground water table outside the SAT system. In Figure 3D, infiltration basins are clustered together and surrounded by a circle of wells for pumping the renovated water. However, these wells tend to deliver a mixture of renovated sewage water from the SAT system and native ground water that is drawn from the aquifer outside the SAT system. This could be beneficial where such blending is desired, but objectionable where there are legal restrictions on pumping native ground water. The systems in Figures 3C and 3D allow seasonal rises of the ground water table to store renovated water in the winter and pump it up in the summer. Such seasonal storage is necessary where the renovated water is to be used primarily for crop irrigation.

Pilot projects

There are hundreds of successful artificial ground water recharge projects in the U.S. alone, and many more in the rest of the world. Recharge systems are site-specific and what works well in one place may not be the best in another. Thus, when artificial recharge of ground water is considered in areas where there is no previous experience

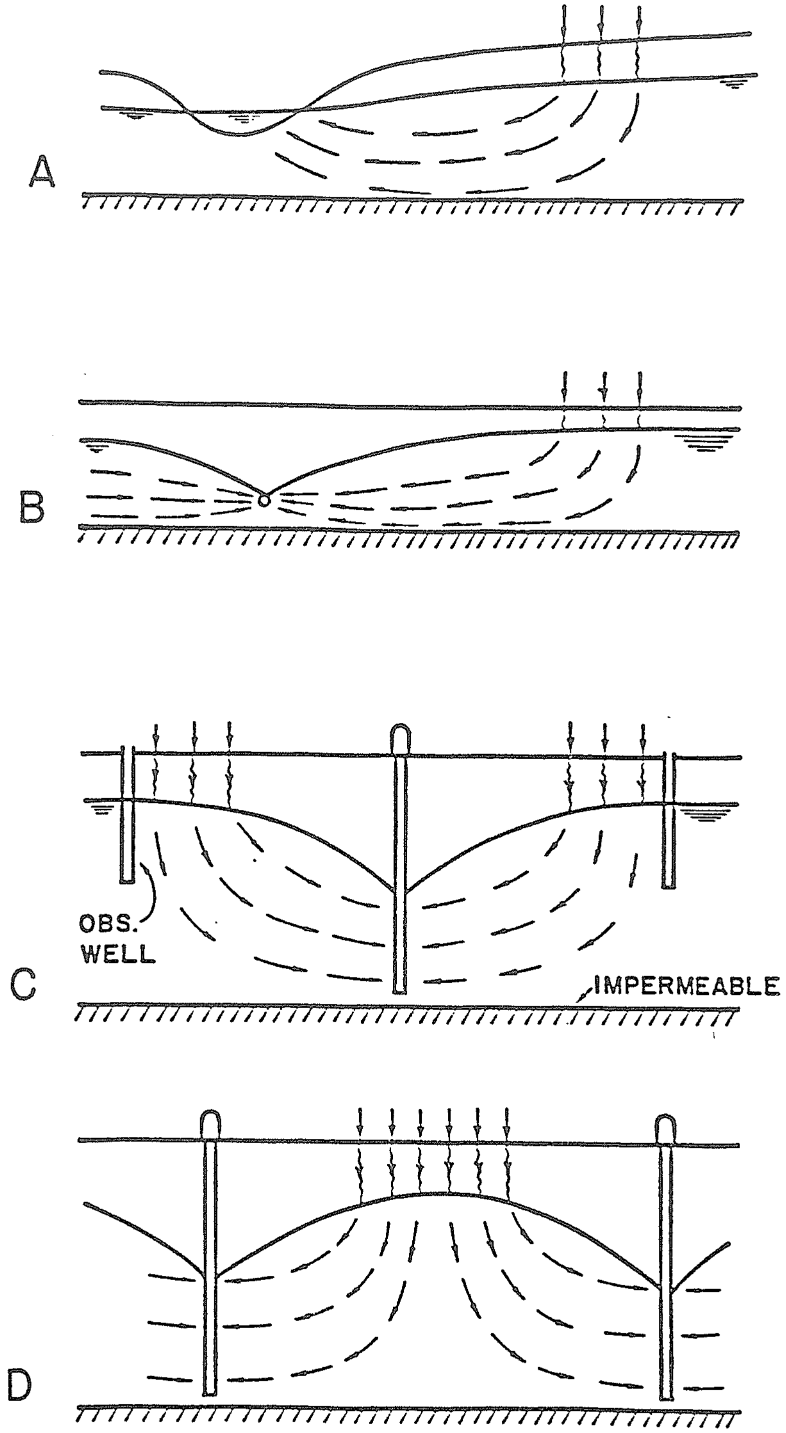

Figure 3. Schematic of soil-aquifer treatment systems with natural drainage of renovated water into stream, lake, or low area (A), collection of renovated water by subsurface drain (B), infiltration areas in two parallel rows and line of wells midway between (C), and infiltration areas in center surrounded by a circle of wells (D).

with such systems, it is always desirable to start with a small project to obtain local experience with artificial recharge of ground water and to develop design and management criteria for the full-scale project. This prevents costly mistakes and can save large amounts of money later on.

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