RENOVATING SEWAGE EFFLUENT BY GROUNDWATER RECHARGE [1]

By

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Sewage effluent is commonly used for irrigation (14). It contains enough nutrients (Table 1) to meet the fertilizer requirements of a number of crops if the sewage supplies all or most of the water for the crop. The most critical use of sewage effluent from a public health standpoint would be sprinkler irrigation of lettuce and other crops that are consumed raw. This requires a well treated effluent, usually consistent with the quality obtainable by secondary treatment and disinfection, to yield total coliform densities of less than 5000 per 100 ml and fecal coliform densities of less than 1000 per 100 ml (13, 14). In some cases, however, the requirements are much stricter. The State of California, for example, requires filtration of coagulated waste water through natural soil or filter media and disinfection to obtain total coliform concentration not exceeding 2.2 per 100 ml before the effluent can be used for sprinkler irrigation of produce (7). Less stringent requirements are generally used for effluent that is used for irrigation of nonedible crops or crops that are processed before they are consumed (7).

Table 1. Normal range of mineral increase in water by one cycle of domestic use (6).

	Parts per Million	Pounds per Acre-foot
Total salts	100-300	270-820
Boron (B)	0.1-0.4	0.3-1.1
Sodium (Na)	40-70	110-190
Potassium (K)	7-15	19-41
Magnesium (Mg)	3-6	8-16
Calcium (Ca)	6-16	16-44
Total nitrogen (N)	20-40	55-110
Phosphate (PO_4)	20-40	55-110
Sulphate (SO_4)	15-30	41-82
Chloride (Cl)	20-50	55-140
Alkalinity (as $CaCO_3$)	100-150	270-410

If more sewage water is applied than needed for crop growth, the excess water will move deeper into the ground to become "renovated" water, which can be allowed to move naturally to streams or lakes, or can be collected with wells or drains for rather unrestricted reuse. Sometimes, waste water renovation is the major objective of land disposal, and agricultural use of the disposal fields is of secondary importance, particularly if permeable soils are available so that large land areas are not required. Another objective of land disposal systems could be to keep the waste water out of streams or lakes, to reduce pollution of surface water.

Because of the increasing need for using sewage effluent for purposes with a higher economic return than irrigation of nonedible crops, interest in land application as a form of tertiary treatment is rapidly increasing. The waste water would then be used for groundwater recharge, employing basins, furrows, or sprinklers to infiltrate the water into the soil, and drains or wells to collect the renovated water for unrestricted irrigation, recreation, and industrial and municipal uses.

The performance of a system for renovating waste water by groundwater recharge depends on the local conditions of climate, soil, and groundwater. An experimental project is therefore, frequently desirable to obtain design information for the operational system so that renovated water with the desired quality can be obtained at minimum cost. An example of such a pilot facility is the Flushing Meadows Project near Phoenix, Arizona, which will be discussed in the following sections.

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Reuse of Sewage Effluent in the Salt River Valley

Most of the sewage effluent of the cities in the Salt River Valley is treated by the 91st Avenue Plant, which is an activated sludge plant handling sewage from Phoenix, Tempe, Scottsdale, Mesa, and Glendale. The plant discharges some 50 mgd of secondary effluent which may increase to about 250 mgd by the year 2000. At 4.5 feet average annual water use, this could irrigate about 70,000 acres, which may be more than the agricultural land remaining in the Salt River Project at that time. The urban waste water would thus be sufficient to meet all agricultural demands in the not too distant future while leaving some for recreation and other purposes.

Because of the varied agriculture and the use of canal water for irrigation of parks, playgrounds, private yards, and for recreational lakes, large scale return of sewage effluent to the canal system requires that the effluent be given tertiary treatment. Since the hydrogeological conditions in the Salt River bed are favorable for groundwater recharge, the most economical way for renovating the sewage effluent could be by groundwater recharge with infiltration basins in the river bed. This bed is normally dry below Granite Reef dam (a diversion structure 25 miles east of Phoenix) and it attains a width of about one-half mile in the western part of the valley. The movement of the effluent water through the sands and gravels of the river bed could be expected to remove essentially all biodegradable materials and microorganisms and to reduce the concentration of other substances in the effluent. This would yield a renovated water suitable for unrestricted irrigation, primary-contact recreation, and other purposes.

To study the feasibility of renovating sewage effluent by groundwater recharge, an experimental project, called the Flushing Meadows project, was installed in 1967. The project is located in the Salt River bed about 1-1/2 miles west of 91st Avenue. It is a cooperative effort between the U. S. Water Conservation Laboratory of the U. S. Department of Agriculture and the Salt River Project, and it was partially supported by a grant from the Federal Water Quality Administration.

Flushing Meadows Project

Description of System

The project contains six parallel recharge basins, 20 x 700 ft each and spaced 20 ft apart (Figure 1). Secondary effluent is pumped from the discharge channel of the 91st Avenue treatment plant into the basins at one end where the flow is controlled by an alfalfa valve and measured with a triangular, critical depth flume (10). The water depth in each basin is controlled by an overflow structure at the other end, where the outflow is measured with another flume. Water depths of 0.5 and 1 ft have been used. The infiltration rate for each basin is calculated from the difference between the inflow and the outflow rates.

The soil beneath the basins consists of about 3 ft of fine, loamy sand underlain by a succession of coarse sand and gravel layers to a depth of 240 ft where a clay deposit begins. The original saturated hydraulic conductivity of the fine, loamy sand top layer was about 4 ft/day. The underlying sand and gravel layers, which have been described in detail (3), can be considered as one anisotropic medium. The hydraulic conductivity of this medium is 282 ft/day horizontally and 17.6 ft/day vertically. These values were obtained by electrical analog analysis and confirmed by permeability tests on the observation wells in the project area (3). The static groundwater table is at a depth of about 10 ft. Observation wells consisting of 6-inch diameter cased holes open at the bottom were installed at various locations in the project area (Figure 1). These wells, which range from 20 to 100 ft deep, are used to obtain samples of the reclaimed water for chemical and bacteriological analyses and to measure the response of the groundwater level to groundwater recharge.

In conformance with the theory of groundwater mound formation below infiltration basins (1), the groundwater level rises rapidly after the start of a new inundation period, but reaches a pseudoequilibrium level in a few days. When a dry-up period is started, the groundwater levels recede and reach their original levels in a few days. Because of the high hydraulic conductivity in horizontal direction of the aquifer, the height of the groundwater mound during recharge is relatively low, i.e., 1.09 ft per 1 ft/day infiltration rate.

Infiltration Rates

To evaluate the effect of surface condition of the basins on infiltration rate, one basin was covered with a gravel layer, another was left in bare soil, and the four remaining basins were planted with bermudagrass in 1968. Inundation schedules ranged from 2 days wet and 3 days dry to 3 weeks wet and 3 weeks dry (periodic drying of the basins is necessary to restore infiltration rates and to allow oxygen to enter the soil). The infiltration rates were generally between 1 and 4 ft/day, depending on the water depth, the suspended solids content of the effluent, and the length of the inundation and dry-up periods. During inundation, the infiltration rate usually decreased almost linearly with time. Tensiometer measurements in the soil beneath the basins and measurements of the effect of water depth in the basins on the infiltration rate indicated that the decrease in infiltration during inundation was mostly caused by clogging at the soil surface.

After accounting for the soil variability between the basins, the infiltration in the grass basins was about 20% higher, and in the gravel-covered basins 50% lower, than in the bare soil basin (4). The higher infiltration rates in the grass basins were attributed mainly to the prevention of algal growth on the bottom of the basins. The low infiltration rate in the gravel basin was probably caused by poor drying of the soil beneath the gravel with consequent slow recovery in the infiltration rate.

Maximum hydraulic loading or long-term infiltration was obtained with inundation periods of about 2 weeks and dry-up periods of about 10 days in the summer and 20 days in the winter. With this schedule, the average accumulated infiltration for the year 1970 was 400 ft. Thus, one acre of recharge basin can renovate 400 acre-feet per year, or 0.36 mgd.

Quality Improvement of Water

The East Center Well (ECW, Figure 7) is 30 ft deep. Water pumped from this well has traveled vertically about 8 ft from the basin bottom to the groundwater table, and 22 ft from the water table to the bottom of the well. Since the well is located midway between basins 3 and 4, the water has also traveled about 10 ft horizontally. The time required for this travel ranged from 1 to 2 weeks, depending on the infiltration rate. Quality parameters of the water from this well, which receives reclaimed sewage water that has infiltrated in basins 3 and 4, and of the reclaimed water from the 20-ft-deep wells 1 and 7 outside the basin area (Figure 1) are shown in Table 2 in relation to the quality of the sewage effluent (see also (4)).

Oxygen Demand

The data in Table 2 show that the 5-day BOD of the reclaimed water is essentially zero. The chemical oxygen demand (COD) is reduced from 50 to 17 ppm, which is about the same as the COD of the native groundwater.

Nitrogen

The nitrogen in the effluent is almost all in the ammonium form. This is mostly converted to nitrate in the reclaimed water if sequences of short inundation periods (2 days wet - 3 days dry) are used. With longer inundation periods (2 weeks wet - 2 weeks dry), nitrate nitrogen concentrations in the reclaimed water are much lower (Table 2), with those below the grass basins being lower than those below the nonvegetated basins. In 1968, for example, the NO_3-N concentration in ECW-water during sequences of long inundation periods dropped from about 10 ppm to about 0.2 ppm after the bermudagrass had reached maturity in basins 3 and 4, but the NO_3-N concentrations in the water from well 1-2, which had infiltrated in the nonvegetated basins 1 and 2, remained in the 5- to 10-ppm range.

The dependence of the NO_3-N concentration in the reclaimed water on the length of the inundation period is illustrated in Figure 2, which shows that for the short inundation periods in July and August 1968 the NO_3-N concentration was about 21 ppm. For the long inundation periods for the rest of the year and with full grass cover in basins 3 and 4, NO_3-N concentrations were close to zero after the passage of a NO_3-peak. This peak, which always occurred a few days after the start of a new inundation period when sequences of long inundations were held, is due to the arrival of nitrified sewage water that was held as capillary water in the soil during the preceding dry-up period. Also, nitrate may have been formed by nitrification of ammonium held by the exchange complex in the soil. The

NO_3-peak arrived in ECW from 5 to 11 days after the start of an inundation period, depending on the infiltration rate in the basins. Thus, the underground detention time of the water pumped from ECW is in the 5- to 11-day range. At greater distances from the recharge basins, the peaks become less distinct.

Table 2. Chemical and bacteriological parameters (average values) of secondary effluent and reclaimed sewage water from observation wells (in milligrams/liter, except for pH and coliform density).

(1)	Effluent (2)	ECW (3)	Well No. 1 (4)	Well No. 7 (5)
BOD_5	15	0.3		
COD	50	17	14	14
Organic N	1	trace		
NH_4-N	25	10	3	1
NO_3-N	0.1			
short inundations		15		
long inundations (bare)[a]		9		
long inundations (grass)[b]		0.2		
PO_4-P	13	5	1.5	1.5
F	4.5	2.5	1.7	2.1
B	0.7	0.7	0.7	0.7
Dissolved salts	1020	1060		
pH	7.9	7.2	7.7	7.4
Fecal coliforms (MPN/100 milliliters)	10^6	20[c]		10[c]

a - reclaimed water below bare-soil basins
b- reclaimed water below grass-covered basins
c- median value (range 0-100)

The NH_4-N content of the reclaimed water usually ranges from 5 to 15 ppm and apparently is not much affected by the length of the inundation periods used at the Flushing Meadows Project. Thus, before and after the passage of the NO_3-peak, the total nitrogen in the reclaimed water during long inundation periods in the vegetated basins is about 40 to 80% less than that in effluent.

The nitrogen behavior in the renovated water is probably due to adsorption of ammonium by the clay and organic matter in the soil, which could begin after the start of an inundation period when oxygen for nitrification is no longer available. Before the adsorption capacity for ammonium is reached, the basins should be dried. The presence of oxygen in the soil will then cause nitrification of the adsorbed ammonium. Part of the nitrates formed in this process can subsequently be denitrified, either during dry-up or during the next inundation, with the nitrogen gas escaping to the atmosphere or moving out as dissolved nitrogen with the downward moving water. Storage of nitrogen in the soil was small and could not account for the amounts of nitrogen removed from the sewage water.

Continued use of long inundation periods for nitrogen removal apparently caused the cation exchange capacity of the soil to become saturated with ammonium, because the ammonium levels in the renovated water began to increase if long inundation periods were used for a few years. Additional lateral movement of the renovated water below the water table may be effective in removing some of this ammonium. However, it is probably more desirable to restore the nitrogen-removing capacity of the recharge system by changing to a sequence of short, frequent inundation periods. The resulting nitrification of the adsorbed ammonium then restores the ability of the cation exchange complex in the soil to adsorb ammonium. The same may be achieved by using some extra long dry-up periods in the summer so as to allow the soil to dry to lower water contents, which increases the oxygen diffusion rate and hence the depth of the aerobic zone. Growing a crop may also be effective in restoring the nitrogen-removing capability of the soil system, not only because the crop will remove nitrogen from the soil but the moisture uptake by the roots will increase the oxygen diffusion rate and hence the depth of the aerobic zone. The root zone could also contribute to denitrification.

Phosphates

Phosphorus, which occurs mainly in the form of orthophosphates in the effluent, is reduced from about 13 ppm P in the effluent to about 5 ppm P in the reclaimed water from ECW (Table 2). Further reductions in P-content occur with additional lateral movement of the reclaimed water below the water table (see P-contents for wells 1 and 7 in Table 2). Extrapolation of the P-removal in relation to distance of underground travel shows that at a distance of about 100 to 200 ft from the recharge basins, very small P concentrations can be expected.

In the sandy and gravelly materials of the Flushing Meadows Project, P probably is removed by precipitation of calcium-phosphate complexes such as apatite. Assuming that all P is precipitated as apatite in a soil volume 30 ft deep and 4 times as wide as the width of the recharge area, the apatite would occupy 0.5% of the total volume after a period of 200 years. Assuming a porosity of 20%, the apatite would thus take up about 2.5% of the pore space. This is small and will likely not have a significant effect on the hydraulic conductivity of the aquifer. If the soil is rich in iron and aluminum oxides, high rates of P-removal can be expected over shallow depths of soil (8, 12).

Fluorides

The removal of fluorides also continues as the water moves laterally below the water table, as indicated by the lower F-concentrations in wells 1 and 7 than in ECW, which in turn contains about half as much fluorides as the effluent (Table 2). Fluorides may be adsorbed on clay minerals (5) or be precipitated as fluor-apatites or calcium fluoride.

Boron

The boron concentration is about 0.7 ppm and remains unchanged as the water moves downward through the soil and laterally below the water table (Table 2). Thus the sands and gravels appear to contain few aluminum and iron oxides, which are effective in remvoing boron (11). Boron concentrations above 0.5 ppm in irrigation water can be damaging to some of the more sensitive crops such as citrus, stone and pome fruits.

Salts and pH

The average salt concentration of the reclaimed water is 1060 ppm, which is about 4% higher than that of the sewage effluent (Table 2). This can be attributed to evaporation from the water in the recharge basins (average annual evaporation from a free water surface in the Phoenix area is about 6 ft). The pH of the reclaimed water is somewhat lower than that of the sewage effluent (Table 1), probably because of CO_2 production by the soil bacteria.

Coliform Density

The total coliform density in the reclaimed water from ECW, determined weekly with the multiple-tube fermentation technique, was higher during sequences of inundation periods of 2-3 weeks than during inundation periods of 2-3 days, i.e., median MPN-values were about 200 per 100 ml for the long periods and 5 per 100 ml for the short periods.

The fecal coliform density in the reclaimed water was very low and often zero (Table 2). The number of fecal coliforms tended to increase somewhat after the start of a new inundation period when newly infiltrated water had arrived at the bottom of the well. The same trend was true for the presumptive MPN of coliforms, which sometimes reached a value of several hundred per 100 ml. After the end of an inundation period, the presumptive MPN of coliforms in the ECW water generally decreased and reached a value of close to zero in about 3 weeks. Therefore, it is concluded that an additional underground detention time of about 1 month should be sufficient for essentially complete removal of all coliform organisms. Regrowth of nonfecal coliforms, such as *Aerobacter aerogenes* in sewage water as it moves through the ground has sometimes been observed (9).

Economic Aspects and Large-Scale System

The cost of reclaiming water from sewage effluent or other liquid waste by soil percolation and groundwater recharge depends on the climate and on the topographic and hydrogeologic conditions. On flat land, the effluent may be applied by basins or furrows. On sloping land, contour furrows or sprinkler systems may be used. Where the infiltration rates are low, large land areas may be required and it may be more economical to combine the recharge system with agricultural utilization of the land (2, 8, and references therein).

The design of groundwater recharge systems for waste water reclamation should be based on three criteria: (a) avoiding a rise of the groundwater table below the recharge basins above a certain maximum elevation, (b) locating the facilities for collecting the reclaimed water (wells, drains, or trenches) a certain distance from the recharge areas to allow sufficient time and distance of underground travel for the reclaimed water, and (c) minimizing the spread of reclaimed water into the aquifer outside the recharge system. For a more detailed discussion of the design of recharge systems for renovating waste water and of techniques for evaluating hydraulic properties of aquifers and predicting water table positions and underground detention times, reference is made to (3).

For the Salt River bed, recharge basins could be located on both sides of the river bed (Figure 3). The distance between the two recharge strips would be about 1000 ft. Wells for pumping the reclaimed water could be placed in the center of the river bed, thus insuring a minimum underground travel distance of about 500 ft for the renovated water. With an annual infiltration of about 330 ft in the basins, about 900 acres of recharge basins would be required to renovate the annual volume of 300,000 acre-feet of sewage water expected by the year 2000. The cost of reclaiming the sewage water in this manner is expected to be about $5 per acre-foot, including amortization of capital investment and operating and pumping costs. The cost of in-plant tertiary treatment to obtain reclaimed water of similar quality would be at least ten times as much (2 and references therein).

Summary

Due to continued population growth in the Salt River Valley, Arizona, reuse of municipal waste water becomes essential. A pilot project was installed in 1967 to determine if the tertiary treatment necessary to permit large-scale reuse of sewage water for irrigation and recreation could be obtained effectively and economically by groundwater recharge with infiltration basins in the normally dry Salt River bed. The hydrogeological conditions of the Salt River bed, i.e., about 3 ft of fine, loamy sand underlain by sand and gravel layers to great depth and a groundwater table at about 10 ft depth, are favorable for high-rate waste water reclamation by groundwater recharge. Results so far indicate that the infiltration rate in grass-covered basins is 25% higher, and in a gravel-covered basin 50% lower, than in a bare soil basin. Alternating 2-week inundation periods with 10-day dry-up periods (17 days in winter) yields an annual infiltration rate of about 400 ft.

Reclaimed water, pumped from 30 ft depth in the center of the recharge area, has a biochemical oxygen demand of about 0.5 mg/liter (BOD of the sewage effluent is about 15 mg/liter) and a median fecal coliform density of 10 per 100 ml. Nitrogen, which is almost all in the ammonium form at a concentration of 25 ppm N in the sewage effluent, is essentially all converted to the nitrate form in the reclaimed water if sequences of short inundation periods (3 days or less) are held. With inundation periods of 2 to 3 weeks, the reclaimed water has about 40 to 80 percent less nitrogen than the sewage effluent, except for a short period occurring 1 to 2 weeks after the start of a new inundation, when a nitrate peak occurs in the reclaimed water. This peak is due to the arrival of nitrified effluent water held as capillary water in the soil during the preceding dry-up period. The nitrogen removal is probably mostly due to denitrification and adsorption of ammonium in the soil. More nitrogen was removed under vegetated infiltration basins than under non-vegetated basins.

Phosphate concentrations in the reclaimed water pumped from 30 ft depth in the center of the recharge area are around 5 ppm P, as compared to 13 ppm in the effluent. Further horizontal movement of the reclaimed water below the water table gives additional reduction in the phosphate content, as indicated by the concentration of 1.5 ppm P in the water pumped at 100 ft distance from the infiltration basins. Fluorides are reduced from 4.5 ppm in the effluent to 2.5 ppm at 3 ft depth in the center of the area and to 1.9 ppm at 100 ft from the basins. Boron removal does not take place because the sands and gravels contain little or no iron or aluminum oxides. The boron concentration is around 0.7 ppm, however, which is slightly above the level where the yield of the more sensitive crops will be affected when the water is used for irrigation.

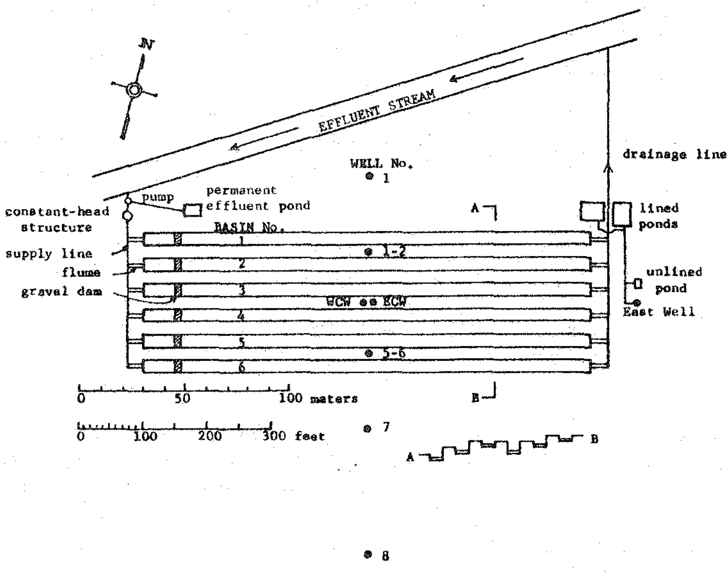
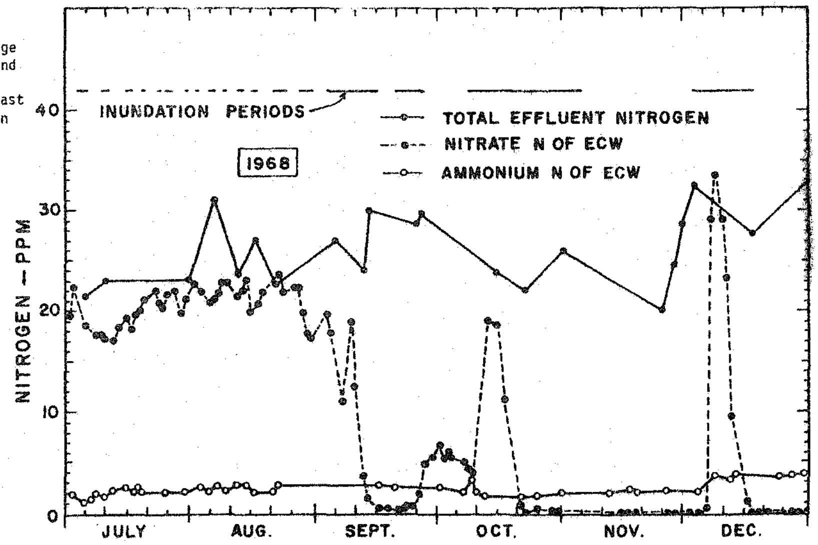


Fig. 1. Plan of Flushing Meadows Project.

Fig. 2. Total nitrogen in sewage effluent and nitrate and ammonium nitrogen in reclaimed water from East Center Well in relation to schedule inundation (July-December 1968).



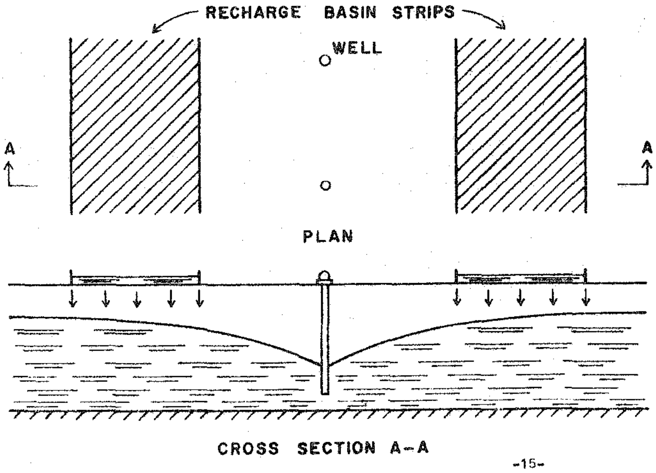


Fig. 3. Plan and cross section of two parallel recharge strips with wells midway between strips.

To reclaim the sewage flow of about 300,000 acre-feet per year that is expected in the Phoenix area by the year 2000, about 900 acres of infiltration basins would be required. These basins could be located on both sides of the Salt River bed. The reclaimed water would be pumped up by wells in the center of the river bed. The minimum underground travel distance and detention time would be about 500 ft and 1 month, respectively. Cost of reclaiming water in this manner would be about $5 per acre-feet, which is less than one-tenth the cost of equivalent, in-plant tertiary treatment.

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