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Source: *Journal (Water Pollution Control Federation)*, Feb., 1974, Vol. 46, No. 2 (Feb., 1974), pp. 260-270

Published by: Wiley

Stable URL: https://www.jstor.org/stable/25038122

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Artificial groundwater recharge is practiced primarily as a method of conservation of groundwater resources. The reuse of wastewater through artificial groundwater recharge is a natural extension of this conservation. In addition, it can help retard eutrophication of surface waters through water quality improvement by physical and biological processes in the soil.

Because of the nature of treated wastewater, most authorities consider its direct reuse to be esthetically unacceptable and possibly not wise from the standpoint of public health.[1-7] Many investigators have observed an improvement in the chemical, bacteriological, and viral quality of recharged wastewater effluent after movement through the soil.[2-4, 7-16] By mixing and dilution with native groundwaters, the concentration of individual constituents, as well as the total dissolved solids content, may be reduced. The amount of dilution depends on the proportions of natural infiltration and artificial recharge, as well as the chemistry of the native and recharged waters. Some authors stress the need for the recharged water to remain in the groundwater system for a given period of time in order for the recharged water to obtain the characteristics of groundwater.[7, 9, 12] Presumably the stated times are necessary for the biological, physical, and dilutional processes to occur.

According to Todd,[17] as of 1970 more than 400 cities in the U. S. were using treated effluent for agricultural irrigation or for groundwater recharge. In most of the instances where irrigation is practiced, some of the effluent recharges the groundwater reservoir. The deliberate recharge of treated wastewater effluent is a recent development in the U. S. As recently as 1958 it was reported, "Treated sewage or waste effluent are not used in any state for the specific purpose of recharge."[18] Since that time, wastewater recharge has been practiced in Santee,[2-4] Whittier Narrows,[5, 6], and Orange County,[1, 19, 20] Calif., and the University of Pennsylvania.[15, 16] Additional research and pilot projects have been carried out at Phoenix,[7, 14] and Tucson,[21] Ariz., Bay Park[8, 22-30] and Riverhead,[22, 27, 31-33] N. Y., San Francisco,[34] Calif., and the Hyperion treatment plant,[35] as well as in Israel.[10, 11] In addition, research and experience have been reported on the recharge of highly polluted river water and biologically active surface water that can react similarly to treated wastewater effluent.[9, 12, 13, 36-40]

Aquifer Recharge Through Open Basins

Open basins are fairly inexpensive to construct and simple to operate. However, they can be used to recharge only aquifers that have a direct hydraulic connection with the ground surface. Design values are well known. Such basins have been used, for example, on Long Island, N. Y., for artificial recharge using stormwater[41-44] and in Peoria, Ill., using river water.[45-47]

Infiltration rates. A wide range of infiltration rates for recharge basins has been reported. According to American Water Works Association Task Group 2440R, basin infiltration rates of 0.09 to 200 ft (0.03 to 61 m)/day have been reported in the U. S.[48] Wastewater effluent has been recharged at rates of 1 to 3 ft (0.3 to 0.9 m)/day at Phoenix[7] and at average rates of 1 ft (0.3 m)/day at Hyperion,[35] and

Santee.[4] River water is recharged at rates of 3 to 15 ft (0.9 to 4.6 m)/day in Sweden,[12] 0.5 to 1.5 ft (0.15 to 0.46 m)/day in Holland,[9] at a design rate of 8 ft (2.4 m)/day in Germany,[21] and at Peoria, Ill., rates as great as 200 ft (61 m)/day have been observed,[49] although annual recharge was about 20 to 100 ft (6.1 to 30.5 m)/day.

The initial infiltration rate of a recharge basin is a function of the soil permeability, permeability of the surface layer, moisture content of the underlying beds, basin slope, depth of water in the basin, water temperature, amount of suspended solids (ss), and other undefined factors. Although it can be modified somewhat in basin design, it is essentially a fixed property of local geologic conditions.

The initial infiltration rate can be decreased by several factors. If the groundwater mound beneath the basin rises to the bottom of the basin, it could reduce the infiltration rate. This might occur when the initial water table is close to the surface and the amount of infiltration is great. The height of the groundwater mound can be computed from theoretical considerations, and this should be done if such a problem is anticipated.[50, 51]

Soil clogging. Physical clogging of the surface layers of the soil in the recharge basin can reduce the infiltration rate. Behnke[49] investigated the clogging of recharge basins by mechanical particles. Turbid waters were applied to sand columns. Within 8 hr observable clogging occurred at turbidities as low as 50 mg/l. The clogging was observed to be essentially a surface sealing phenomenon. The more important variables included the size distribution of the particles in the water relative to the pore size of the soil and the concentration of the material in suspension.

Physical clogging of the soil surface has been observed in the Peoria, Ill., recharge pits.[19, 45–47] Although the soil surface has been renewed periodically, penetration of the sediment into the aquifer pores has reduced the permeability of the aquifer and permanently lowered the infiltration rate of the recharge pits. Although the surface layers of recharge basins can be replaced or renewed, the surface layer should be sized so that physical particles (silt and clay) cannot enter the aquifer material.[7]

Biological growth can also reduce the infiltration rate of recharge basins. Algae may grow in a recharge basin. Dead organisms can accumulate on the bottom, causing the surface to clog in much the same manner as particles of mineral matter.[7, 9, 12, 13, 33, 40, 48, 52] In some water, algae growths can precipitate calcium carbonate and bacteria can precipitate iron salts, which can effectively seal the bottom.

Algae control through the use of an algaecide, CA-350, which contains 300 ppb Cu and 50 ppb Ag, was studied at Sojovice, Czechoslovakia.[40] Algae growth was controlled with dosage at the aforementioned levels, although copper eluted from the test filters at a rate up to 0.17 mg/l. There were no observed harmful effects on the bacteria, and aerobic decomposition of the organic matter occurred.

Algae can also be controlled by the intermittent drying of the basin surface.[18, 48, 53] Because this is one of the commonly accepted methods of restoring infiltration capacity, the required frequency might also meet the requirements for algae control. Bouwer[7, 14] investigated the effects on infiltration rates of various basin bottom materials, including bare soil, gravel, and grass. He found the lowest infiltration rates to be in the gravel bottom basins and the highest in the basins with grass in the bottom. The high infiltration rates of the grass-bottom basins were attributed to a reduced algae growth caused by shading of the bottom by the grass. The intermittent application of water also helps to control the growth of mosquitoes and midges, which may occur in standing water.

Studies by Nevo and Mitchell[39] using artifical wastewater showed that biological clogging during recharge was caused by the accumulation of microbial polysaccharides (complex sugars). This was accompanied by a reduction in the measured oxidation potential in the sand. Periodic resting of recharge beds was found to restore aerobic conditions and renew the infiltration rate of the recharge bed. Paddy rice, which releases oxygen from its roots, was found to be effective in keeping the sand oxidized. It was also found that soils with large pore spaces recovered their infiltration capacity more slowly than those with small pore spaces. This indicates that fine sand might be better for recharge than coarse sand. Amramy [10, 11] noted that organic matter accumulated in the top 4 in. (10 cm) of soils receiving wastewater effluent. There was no progressive buildup of organic matter beyond this depth, even with the passage of time. He determined that, under the conditions in Israel, a cycle of 2 or 3 days of wetting and 7 to 8 days of drying produced the best infiltration results. It was found that by passage through 262 ft (80 m) of the aquifer, BOD was reduced by 90 percent, organic nitrogen by 63 percent; total nitrogen decreased by 64 to 80 percent. Nitrate at the sampling point averaged 16.2 mg/l while the average total nitrogen was 34.2 mg/l in the spreading basin.

Pollutant removal. Bouwer [7, 14] also found a very significant reduction in total nitrogen. This reduction is apparently related to the length of the wetting cycle. With a short cycle (2 days wet, 3 days dry), all of the nitrogen was oxidized to nitrate in the renovated water. However, a long cycle (14 days wet, 7 days dry) yielded about a 90 percent removal of total nitrogen.

Nitrogen removal by soil mechanisms was discussed by Lance.[54] Physical removal occurs through adsorption by clay and organic matter as well as cation exchange with clay minerals. Volatilization of ammonia may release a small amount of gaseous ammonia. Biological denitrification producing nitrogen gas may also occur. This is the system with the greatest potential for being an effective means of nitrogen removal over a long term artificial recharge project.

At Santee, Calif., total nitrogen in the treatment plant effluent was 310 lb (140 kg)/day, in the oxidation pond effluent it was 160 lb (73 kg)/day, and in the renovated water after percolation 7 lb (3.2 kg)/day. Removal of phosphorus was from 62 lb (28 kg)/day in the plant effluent to 1.4 lb (0.6 kg)/day in the renovated water.[4] No mechanisms for removal are suggested. It was found that the removal of virus was 100 percent effective with the passage of the water through 400 ft (123 m) of aquifer.[2] Percolation was also effective in removing bacteria at Santee [4] and Phoenix.[7]

The ability of viruses to travel through soil strata is a subject that has not been thoroughly researched to date. The prevalent conclusion is that viruses can travel only very limited distances in sand or silty soil strata. This is based to a great extent on the inability of easily monitored bacteria of the coliform group, or chemicals, to travel. Robeck *et al.*[55] reported on experiments approximating groundwater flows that showed effective virus removal as a result of filtration at natural ground movement rates. They further concluded that removal resulted from contact with the sand particles and not from die-off.

Investigative work undertaken in connection with recharge of reclaimed secondary effluent at the Hyperion Plant in Los Angeles County [56] included monitoring for the presence of enteric viruses in the treated wastewater during the period when the county was embarked on a large scale, mass poliomyelities immunization program using live attenuated virus. The results obtained during this severe test led the investigators to conclude that there would be little if any probability of human enteric viruses penetrating beyond the recharge water.

Clark and Chang [57] and others have listed a number of outbreaks of infectious hepatitis that involved groundwater supplies. These studies indicate that the virus contaminated water traveled anywhere from several to a few hundred ft through the soil to enter the wells, which ranged from shallow to deep. Investigation of these cases revealed that in most cases the virus seemed to have traveled through fissured or fractured substrata rather than through the soil itself.

Drewry *et al.*[58] conducted a series of laboratory experiments using bacterial viruses. From these experiments they concluded that virus movement through a few centimeters of a continuous stratum of soil containing a fairly high percentage of silty or clayey material should present no more, and possibly less, of a public health hazard than movement of pathogenic bacteria. They cautioned, however, that there were definite limitations on using bacterial viruses to serve as models for animal viruses. This study further concluded that virus retention by soils is an adsorption process that is highly effective at pH values below 7.0 to 7.5, but with rapidly decreasing effectiveness at higher pH values. Adsorption was also found to increase with increasing clay and silt content, ion exchange capacity, and glycerol retention capacity. Virus movement through saturated soils apparently was no greater than through unsaturated soils.

ARTIFICIAL RECHARGE THROUGH STREAM BEDS

Matlock [21] describes the recharge of wastewater plant effluent into an ephemeral stream channel at Tucson, Ariz. The effluent received secondary treatment as well as tertiary sedimentation in a holding pond. Normally, most of the effluent is used for non-food crop irrigation, but during October and November the total outflow was diverted to the Santa Cruz River Channel. Average daily flow during the period was 57.8 acre-ft (71,000 cu m)/day. The maximum distance the effluent traveled was 14 to 16 miles(22 to 26 km) in the normally dry channel, which averaged 100 ft (30 m) in width. A 6.3-mile (10-km) stretch of the river was studied intensively. The average infiltration rate was 2.0 ft (0.6 m)/day, although it ranged from 1.8 to 2.2 ft (0.55 to 0.67 m)/day during the 20-day study period.

The infiltration rates in the upper reaches of the channel were observed to be greater than those in the lower channel. Sixty-four percent of the infiltration occurred in the first 42 percent by length of the wetted channel. This was attributed to the greater wetted channel area per unit length, but more importantly to the scouring action of peak flow periods, which removed accumulated sediment and algae growth.

ARTIFICIAL RECHARGE THROUGH INJECTION WELLS

Recharge wells are more expensive to construct and operate than recharge basins. However, they require less land and can be constructed on such public properties as highway rights-of-way and parks. They can also be used to inject water into confined aquifers and are thus useful in forming pressure ridges in coastal areas for the prevention of saline water intrusion.

Recharge wells have been in use for a number of years on Long Island, N. Y.,[58, 59] in Los Angeles, Calif.,[38, 60] Israel,[36] Texas,[61, 62] and other areas.[22] For the most part, the source of the recharge water has been surface water or groundwater. It may have been imported for hundreds of miles, as in California, or pumped locally for cooling, as on Long Island. However, a number of research and pilot studies using renovated wastewater have been made.

In the early 1950's a study on the feasibility of the recharge of effluent was carried out at the University of California, Berkeley.[34] Settled raw wastewater diluted with freshwater was injected into a confined aquifier 4.4 ft (1.3 m) thick at rates as great as 64 gpm (240 l/min).

The Los Angeles Flood Control District studied the recharge of a secondary wastewater treatment effluent as a part of its Hyperion studies of water reclamation.[35] A relatively shallow aquifer, 30 ft (9 m) thick, was recharged for a period of some 20 months. The studies showed that the concept of using treated wastewater for aquifer recharge through wells was feasible.

A major research project in the treatment and injection of renovated water was underway at Bay Park in Nassau County, N. Y. for several years.[8, 22-30] An 18-in. (46-cm) diam well with a 16-in. (40-cm) well screen from 418 to 480 ft (127 to 146 m) below land surface was used for the injection. Preliminary findings of that study[52] revealed that head buildup in the injection well (but not the aquifer) exceeded that predicted by pumping-test data, even though the water injected was of potable quality. It was found that the amount of excessive head buildup in the injection well was strongly dependent on the turbidity of the recharge water. Most of the particulate matter injected was filtered out and retained at or near the aquifer-gravel pack interface. Degasification of the injection water was not found to result in a measureable reduction of clogging of the injection well. The specific capacity of the injection well, which was reduced during injection, was found to be largely restored by pumping. Water recovered from the injection well after each test was very turbid initially and contained high concentrations of iron, phosphate, and volatile suspended solids. Bacterial contents were high. Little change occurred in the chemistry of the injected water as it moved through the aquifer for distances of 20 ft (6 m).

Further tests of well recharge of reclaimed water were made at Riverhead, N. Y.[31-33] Two shallow wells in glacial outwash and an above-ground simulator were simultaneously injected with clear water or reclaimed wastewater. One of the wells was single-cased and screened. The second was double-cased with two concentric screens, the outer screen being against the drilled hole with a gravel pack between the screens.

A series of tests was conducted in which fresh potable water and tertiary treated wastewater were injected separately into the wells to determine the respective clogging rates. In the single-screened well the injection of treated waste resulted in clogging to the point of failure from 13 to 38 days after start of the test. The injection of potable water resulted in an increase in clogging during the first 30 days of the test, with no significant increase in clogging from the 31st to the 36th day, at which time the test ended. A similar 21-day test in the double-cased screened well showed a slight but continuous increase in clogging.

Orange County, Calif., Water District has conducted research on the injection of reclaimed wastewater into confined aquifers.[1, 20] After pilot plant tertiary treatment, reclaimed water is pumped to three multi-cased injection wells. Each injection well is screened in the four aquifers subject to saline water intrusion. Initial studies indicate that a mixture of deep-well water and reclaimed water can be injected without excessive clogging.

Design factors. The design and construction of recharge wells is more critical and complicated than that of recharge basins. Because the well screen area is much less than the area of a typical recharge basin bottom, much higher unit rates of flow are necessary for recharge wells. This can be accomplished by the use of much higher hydraulic (injection) heads than are possible with recharge basins. This means that the well casing, the cement grout, and the formations overlying the well screen must be capable of resisting high pressures during injection and development of the well. Cohen and Durfor[26] outlined the design of the well casing and cement grout for the Bay Park injection well. The possible differential pressures on the fiberglass well casing were evaluated.

It has been suggested that a recharge well should be designed similarly to a water well for the same formation.[63] The earliest Los Angeles County injection wells were non-gravel-packed, cable tool wells. Of the eight constructed in 1952 and 1953, four were no longer in operation by 1963. Of the remaining four, one had been rebuilt and gravel packed and three were in use at a reduced efficiency.[38] From this start, the California recharge wells, which are used to inject Colorado River water, have evolved to modern, reverse rotary, gravel-packed wells. Because noncorrosive materials are most suitable, asbestos cement pipe is used as the casing and vertically slotted asbestos cement well screens also are used. The Bay Park well is a reverse rotary, gravel-packed well with fiber glass casing and a stainless steel, wire-wound screen. The Orange County wells have stainless steel casings and screens and are reverse rotary, gravel-packed wells.

The single-cased well at Riverhead was gravel packed, with 8-in. (20.4-cm) diam cement asbestos well casing and slotted screen. The double-cased well had a 30-in. (76-cm) diam stainless steel screen. The inner casing was 8-in. (20.4-cm) polyvinyl chloride, with an 8-in. (20.4-cm) stainless steel screen. The annular space between screens was gravel packed.

The initial capacity of a recharge well is a function of the aquifer properties, the well screen, gravel pack design, and the skill of the contractor. Johnson and others [64] discuss the design of the gravel pack of a recharge well. After the initial recharge to the well, it will begin to clog.

Clogging. Sniegocki [65] provides the following list of principal causes of clogging of recharge wells:

1. Gas binding or air entrainment in the aquifer.
2. Suspended particles in the recharge water.
3. Bacterial contamination of the aquifer by the recharge water and subsequent clogging by bacterial growths.
4. Chemical reactions between the ground water and recharge water causing precipitation of insoluble products.
5. Swelling of clay colloids in the aquifer.
6. Ion exchange reactions that could result in clay particle dispersal.
7. Precipitation of iron in the recharge water as a result of aeration.
8. Biochemical changes in the recharge water and ground water involving iron reducing bacteria or sulphate splitting organisms.
9. Mechanical jamming of the aquifer, caused by particle rearrangement when the direction of water movement through the aquifer is reversed or excessive injection pressure is applied.

Air entrainment can occur when air bubbles are present in the water as a result of a free fall or when dissolved gases escape from a saturated injection water that is colder than the native groundwater. The gas bubbles, which are mostly nitrogen, clog the aquifer pores. This has been observed in recharge wells in Arkansas,[66] Washington,[67] and Israel.[36] Air entrainment can be avoided by installing an injection pipe in the well with a foot valve below static water level. Degasification at Bay Park produced no noticeable results.[8] At Riverhead, a lower clogging rate was noted with degasified effluent, but a higher injection head was required.

The effect of suspended sediments in the recharge well is similar whether renovated water or fresh water is used. Rahman and others [68] studied the clogging of a fine sand aquifer with sediment-laden water of 100 to 500 mg/l in a model recharge well. They found the rate of clogging to be proportional to the amount of suspended sediment. The larger sediment grains were retained in the fine sand close to the well screen. At Bay Park the clogging rate was also found to depend on the amount of suspended sediment, even though the actual amount of suspended sediment was very low (2 to 10 mg/l). According to Vecchioli and Ku [8]: "These suspended solids contents are very low values, and yet a change of only a few mg/l of suspended matter seems to have an appreciable effect on the excessive head buildup in the injection well."

Rebhun and Schwarz studied the clogging of wells recharging water from a biologically productive lake.[37] The recharge water was very clear, with a turbidity of one Jackson unit, but contained plankton from the lake. They suggest that the clogging of the recharge wells is caused by the formation of a mat of organic matter filtered from the recharge water. Such a mat was also observed in the recharge of wastewater at the Berkeley, Calif., recharge experiment.[34] Although the formation of the organic mat is a physical process, it forms an excellent substrate for the growth of bacteria.

The studies at the University of California, Berkeley, showed that the maximum penetration of coliform bacteria into the aquifer occurred soon after injection started.[34] With the development of an organic filter mat, the bacteria were trapped on the mat and fewer traveled into the aquifer. It was observed that neither an increase in the number of organisms nor an increase in the rate of injection resulted in an increased distance of travel of coliform organisms. The reduction in the concentration of coliform organisms was logarithmically proportional to the distance from the point of injection. The conclusion was reached that bacterial contamination would not necessarily be a limiting factor in the recharge of reclaimed wastewater.

Rebhun and Schwarz [37] noted a tremendous growth of bacteria on the organic filter mat. During backwash of the experimental sand columns, it was found that the total number of coliforms backwashed was at least 1,000 times greater than the number introduced. A similar growth of bacteria has been noted in the Bay Park injection well. Vecchioli [23] reports that with the injection of highly treated wastewater effluent that was chlorinated before injection, bacterial growth occurred. Upon initial pumping to redevelop the recharge well, a turbid, odorous water with high iron, phosphate, and coliform concentrations was obtained. With continuous pumping of the well, the water cleared and the bacteria count dropped to drinking water levels. However, upon surging, another slug of turbid water with high coliform counts would be released from the well. This suggests that the backwash action released organic particles that had been in a stable position.

The organic filter mat is located close to the gravel pack-aquifer interface. This was confirmed in several studies by visual observation of well simulators as well as piezometer measurements in the gravel pack and the aquifer close to the well.[8, 31–34, 37] Redevelopment of wells clogged by bacterial growth has been accomplished by an initial heavy dosage of chlorination followed by surging and pumping.[8, 31–34, 37, 38, 65] Bruington and Seares [38] found that the chlorination of Colorado River water at a rate of 2 mg/l would prevent the biological clogging of recharge wells. However, the high ammonia content of renovated wastewater forms a chloramine complex that interferes with disinfection by chlorine.

Chemical reaction between the injection water and recharge water has been noted as a cause of clogging.[69, 70] Clogging by ion exchange of sodium with soils will occur if the sodium adsorption ratio is greater than a certain value.[69] Because of the high oxygen demand of renovated wastewater, the environment near the well should be reducing and iron precipitation not a problem. The growth of iron bacteria has been noted as a problem in the maintenance of stormwater recharge wells on Long Island.

Other designs. Skodje [71] has suggested the use of recharge shafts with boreholes backfilled with sand for recharge. However, as he recommends that the permeability of the sand not be greater than that of the aquifer, the merits and benefits of such a project are questionable. Scott and Avon [72] compared the cost of recharge wells vesus deep, gravel-packed, filled trenches in areas where an impermeable surface layer exists. They found that while trenches were more efficient hydraulically and economically in the case of shallow impermeable layers, wells become more competitive as the thickness of the impervious top layer increased.

Artificial Recharge Through Spray Irrigation

Wastewater plant effluent is commonly used in the irrigation of non-food crops in a number of water-deficient areas.[73] Although recharge is not generally planned, some of the water usually seeps through the root zone to recharge the groundwater table.[74]

A series of experiments and pilot plant operations using spray irrigation as a method of groundwater recharge has been made at Pennsylvania State University.[15, 16] The purpose of the experiment was twofold. First, other common methods of artificial recharge were not possible because of local geologic conditions. Second, it afforded the wastewater an opportunity to move through the biologically active soil zone. Todd [17] points out that the incorporation of a vegetative zone in the recharge plan offers the greatest potential renovation. The removal of nutrients affords protection from eutrophication to surface waters that may ultimately receive the renovated water.

Secondary effluent was sprayed at a rate of 0.25 in. (0.64 cm)/hr for a total of 1 or 2 in. (2.5 or 5.1 cm)/wk at each location. The system that was used worked satisfactorily at temperatures as low as $-12°F$ ($-24°C$). In order to permit renovation by the soil biota, recharge rates must not be so high that the water moves too rapidly through the soil zone. The 2-in. (5.1-cm)/wk application rate is equivalent to 7,754 gal/day/acre (72,500 l/day/ha). This requires an area of 129 acres/mg (13.8 ha/day/mil l) applied.

During winter operations, care had to be taken so that nutrients were retained in the root zone for use the following summer. The greatest renovation occurred when crop land was irrigated, because the removal of the crops also meant the removal of organic matter from the recharge area. Corn silage was shown to be quite effective in the removal of nutrients. The renovation efficiency of a crop is defined as the ratio of the nutrient removed in the harvested crop to that added in the wastewater. At a 1-in. (2.5-cm)/wk level of irrigation, 200 percent of the total nitrogen, 39 percent of the phosphorus, and 62 percent of the potassium were removed. At a 2-in. (5.1-cm)/wk rate, 105 percent of the nitrogen, 22 percent of the phosphorus, and 40 percent of the potassium were removed. The effectiveness of the recharge was proved when the rate of decline of groundwater levels was reduced near the recharge area.

The Pennsylvania State study differs from most artificial recharge projects in that complete renovation of the wastewater for public health and ecological reasons is a principal requisite. The application rates used are designed to ensure that undesirable constituents in the wastewater effluent are removed in the surface soils by biological, physical, and chemical processes even though this means that the full infiltration capacities of the soil and bedrock limits are not being utilized.

Parizek and Meyers [15] concluded that, in general, regions with established forests and sod will have higher infiltration rates than adjacent cultivated crop land developed on the same soil. They further concluded that the water table should be maintained at a level below the root zone to minimize evapo-transpiration losses. It was estimated that water losses within the biologically active zone might approach 1 in. (2.5 cm)/wk during the growing season at the Pennsylvania State site.

Kardos [15] estimated groundwater recharge for the agronomy area using the Blaney-Criddle method. Recharge in the form of 1- and 2-in. (2.5- and 5.1-cm)/wk applications was equivalent in 1963 to 427,000 and 1,078,000 gal/acre (4 and 10 mil l/ha). This is equivalent to recharge recovery percentages of 65.5 and 82.7. Similar calculations for the year 1964 showed recovery percentages of 59.8 and 79.8 for 1- and 2-in. (2.5- and 5.1-cm) applications. The lower recovery in 1964 was attributed to the severe drought that year. Sopper [75] undertook similar calculations for the forestry area using the Thornthwaite method. These showed that groundwater recharge could have approximated 488,000 and 1,113,000 gal/acre in 1963 (4.5 and 10.4 mil l/ha), based on 1 and 2 in. (2.5 and 5.1 cm) of effluent/wk from mid-May to mid-November. Values in 1964 were 706,000 and 1,602,000 gal/acre (6.6 and 15.0 mil l/ha), respectively. A comparison of 1963 data indicates somewhat greater recharge potential in the forestry area compared with the agronomy area.

Muskegon County, Mich., recently completed an engineering feasibility demonstration study on a wastewater treatment-irrigation system.[76] The study was based on a lagoon treatment-spray irrigation system for the combined domestic wastes and industrial wastewaters. The major portion of the wastewater is from a pulp and paper mill. Unlike the Pennsylvania State studies, the Muskegon studies are based on column filtration tests and a computer simulation model rather than as actual field pilot scale study. The feasibility of using spray irrigation as a means of wastewater renovation and disposal was demonstrated for this project. Shaeffer [77] reported that the Muskegon facility will include storage lagoons to provide for 151 days storage during the winter months. The design flow is 43.4 mgd (164 mil l/day) with a peak capacity of 90 mgd (340 mil l/day). Irrigation will be applied to 6,000 acres (242 ha) of land, with an overall total land requirement of 10,000 acres (405 ha). This is equivalent to 7,233 gpd/acre (67,600 l/day/ha) or a net area of 138 acres/mgd (14.8 ha/day/mil l) applied.

CONCLUSIONS

Artificial recharge of aquifers is a proven method for the conservation of groundwater resources. Research indicates that renovated wastewater may be suitable for recharge. The use of open basins, stream channels, and spray irrigation using present technology is possible with a typical secondary effluent. The amount of maintenance of the facilities depends on the amount of ss in the effluent. Artificial recharge through wells requires a wastewater of much higher quality. Even the slightest amount of turbidity could result in rapid clogging of the well. Bacterial growths may also clog recharge wells. Further research on the rate of well clogging as a function of water quality could result in an improvement in the clogging rate of recharge wells.

Recharge of a fine- or medium-grained aquifer does not seem to lead to any problems from pathogenic bacteria or virus if the water travels several hundred feet. This would not be the case in a fissured aquifer. Water quality improvement may also occur by physical and biological processes that occur in the soil. This is also a fruitful area for further research.

ACKNOWLEDGMENTS

Credits. This work was supported by the Department of Environmental Control, Suffolk County, N. Y.

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