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Zoning Aquifers for Tertiary Treatment of Wastewater

by Herman Bouwer

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ABSTRACT

Soils and aquifers can function as effective and economical filter systems for advanced treatment of conventionally treated sewage and other wastewater. The wastewater is applied to the land with low-rate or high-rate infiltration systems. Physical, chemical, and biological processes in the soil improve the quality of the wastewater as it percolates through the vadose zone and into the aquifer to become renovated water. The quality of the renovated water, however, often is not as good as that of the native ground water. To utilize the land for treatment of wastewater, without trading a problem of surface-water pollution for one of ground-water contamination, the spread of renovated water in the aquifer must be restricted. This can be accomplished by locating the system so that the renovated water drains naturally into a stream or other surface water, or by artificially removing renovated water from the aquifer with wells or drains at some distance from the application area. Examples are given of various systems that utilize these principles, and general design criteria are presented. Proper design involves analysis of underground-flow systems for various system geometries. Methods for measuring hydraulic conductivity, particularly in the vadose zone, are briefly reviewed.

INTRODUCTION

Land application of wastewater in which the pollutants are primarily of organic origin, like conventionally treated sewage and effluents from agricultural processing plants, can be an attractive alternative to additional in-plant treatment. Interest in land application of wastewater is increasing because of:

1. Legal restrictions on the discharge of wastewater into streams, lakes, or other surface water (Clean Water Bill, PL 92-500).

2. Favorable economic aspects, high reliability, and lower energy requirements than comparable in-plant treatment (including advanced techniques).

3. Opportunity for utilization of wastewater for irrigation of crops and use of nitrogen, phosphorus, and other "pollutants" in the water as fertilizer.

4. Opportunity for filtration of wastewater through soils and aquifers to produce renovated water for ground-water recharge. This water can then be reused for unrestricted irrigation, recreation, and other purposes.

TYPES OF SYSTEMS

There are three main types of land application systems: overland flow, low-rate infiltration systems, and high-rate infiltration systems. Overland-flow systems are used when soils are tight and infiltration is slow. Improvement in water quality is obtained primarily by flowing the wastewater in a shallow sheet over a soil surface covered by grass or other dense vegetation. Because of the low infiltration rates, overland-flow systems have little or no effect on the underlying ground water. With low-rate or high-rate systems, the wastewater infiltrates into the soil and the water-quality improvement is obtained as the water moves through the soil and down to the ground water. In low-rate systems, about 2 to 15 cm (1 to 6 inches) of wastewater are applied weekly or every 2 weeks. All systems that utilize wastewater for irrigation fall in this category. The water may be applied with surface-irrigation techniques (borders, furrows) or with sprinklers.

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Surface-irrigation techniques require relatively smooth land, but they require less pumping (energy) and cause less air pollution than sprinkler systems. With high-rate systems, application rates vary from about 50 to 500 cm (2 to 20 ft) per week. Such amounts can be applied by over-irrigating agricultural crops or with special recharge or infiltration basins that generally are not vegetated. Intermittent flooding is the key to successful operation of rapid infiltration basins. Schedules range from 8-hour flooding and 16-hour drying each day to flooding and drying periods of several weeks each.

QUALITY IMPROVEMENT

The movement of wastewater through soil greatly improves its quality through physical, chemical, and biological reactions. Suspended solids are essentially completely filtered out. Bacterial activity in the soil results in almost complete removal of the biodegradable waste matter in the water, as expressed by the biochemical oxygen demand (BOD). However, not all organic compounds are biodegradable and some refractory organics may be present in the renovated water. For sewage effluent, for example, the renovated water may contain about 5 mg/l refractory organics, expressed as total organic carbon. The numbers of bacteria and viruses in the wastewater are greatly reduced, and often completely removed, as the water percolates through soil and aquifer(s).

For low-rate systems, most of the nitrogen in the wastewater is absorbed by crops, which can remove almost 100% of the nitrogen. For high-rate systems, the nitrogen is removed primarily by denitrification in the soil, which can remove about 80% nitrogen and more from secondary sewage effluent, as shown in laboratory studies (Lance *et al.*, 1976). Similar removal rates should be possible for field systems under favorable conditions and with careful management. Otherwise, lower removal percentages can be expected. Phosphates are also taken up by crops or they can be immobilized in the soil, particularly when the soil contains iron and aluminum oxides or is calcareous and alkaline. Phosphates are more mobile in sands with low pH. Immobilization of metal ions in soil is stimulated by pH values greater than 7 and by certain types of clay. Some metal ions, however, may remain in the water and move over long distances, especially when kept in solution by refractory organics that act as chelating agents. For a more detailed discussion of the various physical, chemical, and biological reactions in the soil and the chemical composition of different types of wastewater and renovated water, refèrence is made to Bouwer and Chaney (1974).

Low-rate (irrigation) systems in dry climates yield deep percolation water with a salt content that is about 3 to 10 times that of the original wastewater. Thus, unless the original wastewater has a very low salt content, the deep percolation water from those systems cannot be reused and must be handled like deep percolation or return flow from normal irrigated fields, including removal by drainage and "disposal" into surface water. For high-rate systems, the salt content of the renovated water is about the same as that of the original wastewater.

High-rate systems require relatively deep, light soils, preferably in the sandy-loam to loamy-sand range. Low-rate systems can be used on a wider range of soil textures. Coarse sands and gravels should be avoided. If such materials are also relatively shallow and underlain by fractured or cavernous rock, wastewater could penetrate to ground water in almost unchanged condition. Most of the quality improvement of wastewater in both low- and high-rate systems occurs in the top 1 m (3 ft) of soil. However, additional underground travel and underground detention time should be allowed for "polishing" treatment of the wastewater, including taste-and-odor removal and die-off of microorganisms (Gerba *et al.*, 1975).

ZONING OF AQUIFERS

While the wastewater is greatly improved in quality as it percolates through the soil in well-managed land application systems on properly selected sites, the quality of the resulting renovated water may not be as good as that of the local native ground water, whose quality is thus degraded. To take advantage of the beneficial aspects of land application without trading a surface-water pollution problem for a ground-water contamination situation, the spread of renovated water in the aquifer must be restricted. This can be accomplished by removing the renovated water from the aquifer at some point away from the application area. Sometimes this can be done by locating the land-application system so that the renovated water drains naturally into surface water (Figure 1). Where such a system is not possible, the renovated water can be collected at some distance from the application system by drains if the aquifer is shallow (Figure 2), and wells if the aquifer is deep (Figure 3). The portion of the aquifer between

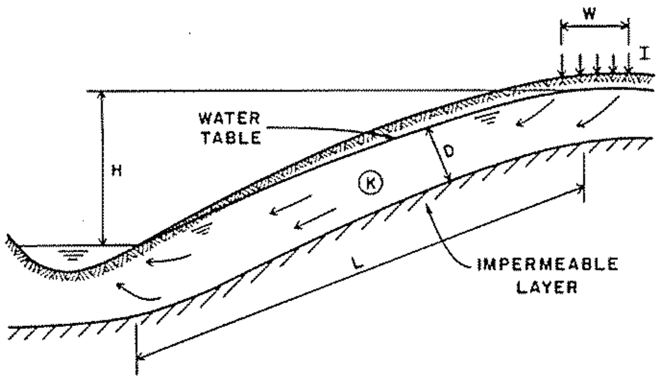

Fig. 1. Natural drainage of renovated water into surface water.

the application system and the discharge point of renovated water is then used as a natural filter system for renovating wastewater. Such zoning of part of an aquifer as a tertiary treatment facility for wastewater is not new. For example, if a certain separation is specified between a well and a septic tank, cemetery, or landfill, the portion of the aquifer in the zone of separation is in fact dedicated to treatment and dilution of the leachate from the pollution source. The difference between this conventional zoning and zoning for land-application systems is that, for the latter, the wastewater is removed from the aquifer after it has become renovated water. The renovated water may be discharged into surface water (through natural drainage or by pumping the discharge from the drains or wells into surface water) for indirect reuse, or it may be directly reused for unrestricted irrigation, unrestricted recreation, and certain industrial applications. Using renovated water for drinking is not yet encouraged, because the possible health effects of the refractory organics and other compounds present in low concentrations in the renovated water are not yet completely understood.

Examples of land-application systems where renovated water drains naturally into a

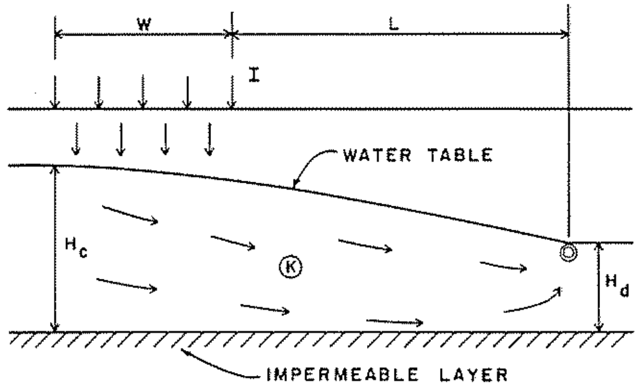

Fig. 2. Collection of renovated water by horizontal drain.

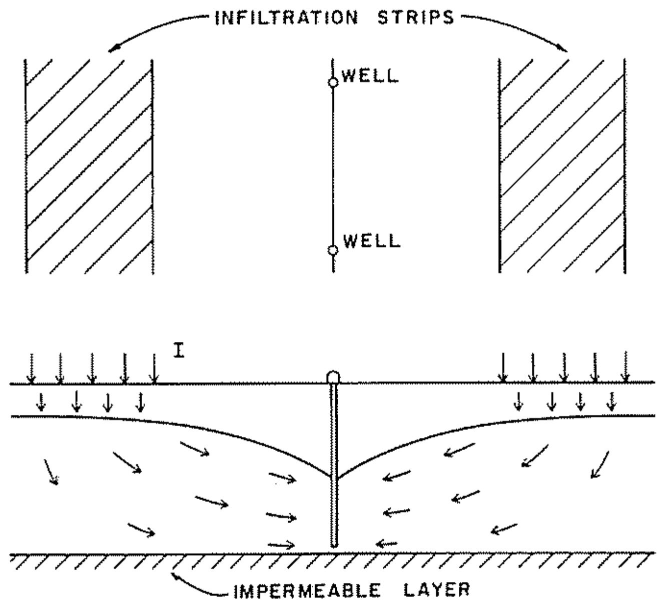

Fig. 3. Collection of renovated water by wells.

stream are the high-rate infiltration systems of Fort Devens, Massachusetts, and Bielefeld, Germany. The wastewater for both systems consists of treated sewage effluent. Renovated water is collected by horizontal drains for the rapid infiltration systems in the dunes of western Holland, where polluted Rhine water is pretreated for municipal water supply, and at Dortmund, Germany, where a similar system is used to pretreat relatively high-quality surface water from the river Ruhr. An open ditch or trench is used at the Santee, California, system to intercept renovated sewage water for use in recreational lakes. Renovated water is collected with wells in the high-rate infiltration systems for Phoenix, Arizona, to enable reuse of the sewage water for unrestricted irrigation and recreation. Restricting the spread of renovated water in the aquifer by drains or wells is easier and less costly for high-rate than for low-rate application systems, because the former require much less land area than low-rate systems of the same capacity.

DESIGN

The design of a system for renovating wastewater by land application and filtration through soils and aquifers, and discharging the renovated water from the aquifer at some distance from the application system, should be based on the following criteria:

1. Ground-water mounds (including perched mounds) must not rise so high during application of wastewater that they restrict the infiltration rate. This can be accomplished by keeping the top of

the capillary fringe above the ground-water mound at least 0.5 m (2 ft) below the surface of the soil or the bottom of the infiltration basin [the corresponding water-table depth will then be about 1 to 2 m (3 to 7 ft), depending on soil texture]. Ground-water mounds should drop to a depth of at least 1.5 m (5 ft) within 2 or 3 days after cessation of wastewater application to permit sufficient aeration of the soil during periods of no infiltration (drying or resting).

2. The design lateral flow in the aquifer between the area of application of wastewater and that of discharge of renovated water should not exceed the flow that the aquifer can handle on the basis of its transmissivity and hydraulic gradients (this applies primarily to systems as in Figure 1).

3. The water must have traveled a sufficient distance underground and must have had sufficient underground detention time before it leaves the aquifer as renovated water. Desired distances and times of underground travel depend on the wastewater characteristics, the nature of the soil and aquifer materials, and the desired quality of the renovated water. For several systems, underground travel distances and detention times are about 100 m (300 ft) and 1 month, respectively (see also Gerba *et al.*, 1975).

Where renovated water discharges naturally into surface water, the lateral flow from the application area to the surface water can be restricted by insufficient aquifer transmissivity. In that case, the product WI of width of infiltration area and infiltration rate must not exceed the product KD H/L of aquifer transmissivity and slope of the water table (Figure 1). When KD H/L is relatively small, the wastewater-application area should be long and narrow so that W and, hence, IW are also small.

Where the renovated water is collected by underground drains (Figure 2), the flow system below the water table can be described by the following equation (Bouwer, 1974):

$$H_c^2 = H_d^2 + IW(W + 2L)/K \qquad (1)$$

where H_c = maximum height of water table above impermeable layer,

H_d = height of water table above impermeable layer at drains (height of center of drains if drains are running free with no back pressure),

I = infiltration rate (average for entire area of width W),

W = width of application area,

K = hydraulic conductivity of aquifer, and

L = distance between edge of infiltration area and drain.

Equation 1 is based on the assumption of horizontal flow, which is valid if H_c is relatively small as compared with W + L. The value H_c should be taken at the outer edge of the infiltration area if the drain is only on one side of the area. However, if drains are on both sides of the infiltration area, H_c refers to the water table below the center of the application strip and W represents one-half the width of the application area. Equation 1 can be used to calculate L for various combinations of W, I, and H_c and H_d so that the best geometry of application area and drain location can be selected. The transient situation, i.e. predicting the rise and fall of ground-water mounds in relation to time, can be handled with equations developed by Marino (1974a and 1974b) for recharge areas bound on one or both sides by surface water with constant water level.

For deep aquifers, the renovated water is more effectively intercepted by wells than by horizontal drains. If several such wells are uniformly spaced on a line midway between two parallel infiltration strips (Figure 3), it is theoretically possible to collect essentially all the water that entered the soil as wastewater. To achieve this, the wells should completely penetrate the aquifer (or at least the upper, active region if the aquifer is deep enough to develop active and passive regions). In addition, infiltration and pumping rates should be managed so that ground-water levels below the outer edges of the infiltration strips are not affected by the infiltration-and-pumping system and remain at the same level as the ground water in the aquifer adjacent to the renovation system. For this purpose, observation wells for monitoring ground-water levels should be installed at the periphery of the system.

To obtain the optimum design of a system such as in Figure 3 (width and length of infiltration strips, distance between strips, distance between wells, and capacity of wells), the water-table drop from the outer edge of the recharge system to the wells should be calculated for various designs so that the best system geometry can be selected. This water-table drop can be predicted by superimposing the ground-water mound formed by infiltration from the recharge strips on the drawdown due to the pumped wells. The rise and fall of ground-water mounds in aquifers of large lateral extent can be predicted with equations or graphs presented by Hantush (1967), Bianchi and Muckel (1970), Hunt (1971), and Singh (1972). Drawdowns around wells can be calculated with conventional well-flow theory. Steady-state solutions for the flow system between the recharge areas and the wells for the geometry of Figure 3 were presented by Bouwer (1970). Equations developed on the basis of horizontal-flow theory should be used with caution where the thickness of the aquifer is larger than the width of the infiltration area, because the lower portions of the aquifer then do not contribute much to the recharge flow system and are essentially stagnant. In those cases, the effective transmissivity of the aquifer for recharge is less than the total transmissivity of the aquifer (Bouwer, 1962).

MEASUREMENT OF HYDRAULIC CONDUCTIVITY

To predict underground-flow systems in connection with land-application systems for wastewater with discharge of renovated water from the aquifer, values of the hydraulic conductivity K in the aquifer and the vadose zone must be known. Such knowledge of K also enables prediction of maximum infiltration rates. Local experimentation, however, is usually required to determine the effect of clogging, biological activity, and weather on infiltration rates, so that a realistic estimate of the infiltration rates can be obtained.

Values of K should preferably be measured in place. The K-values of aquifers can be obtained with pumped-well techniques, like the Theis pumping test, or with the slug test where a volume of water is suddenly removed from a well and the subsequent rise of the water level in the well is measured for calculation of K. The theory for the slug test, which originally was developed for completely penetrating wells in confined aquifers (Cooper, *et al.*, 1967) has recently been extended to partially penetrating wells in unconfined aquifers (Bouwer and Rice, 1976). Point measurements of K, as may be required to detect layers of different K in the aquifer, can be obtained with piezometer techniques (Bouwer and Jackson, 1974, and references therein). For the vadose zone, K may have to be determined in vertical direction to predict effects of restricting layers on perching mounds and to estimate potential infiltration rates. There may also be cases where K of the vadose zone should be measured in horizontal direction, for example, if infiltration will cause the water table to rise and part of the vadose zone will become saturated and contribute to lateral flow of ground water.

The hydraulic conductivity in vertical direction in the vadose zone can be determined with the air-entry permeameter and infiltration-gradient techniques (Bouwer and Jackson, 1974, and references therein). The air-entry permeameter (Figure 4) is essentially a covered infiltrometer with standpipe and reservoir to let the water infiltrate into the soil at high head. The infiltration rate is calculated from the rate of fall of the water level in the reservoir. When the wet front is expected to have reached a depth of about 10 cm (4 inches, equal to the depth of penetration of the cylinder), a valve at the base of the pipeline connecting the reservoir to the cylinder is closed. This halts infiltration and causes the pressure of the water inside the cylinder to decrease until the air-entry value of the soil above the wetting front is reached, after which the pressure of the water inside the cylinder slightly increases. Measuring the minimum water pressure inside the cylinder with, for example, a vacuum gauge with memory pointer, enables the air-entry value at the wetting front to be evaluated. This value is then used to estimate the pressure head at the wetting front while water was still infiltrating. As soon as minimum pressure is detected, the air-entry

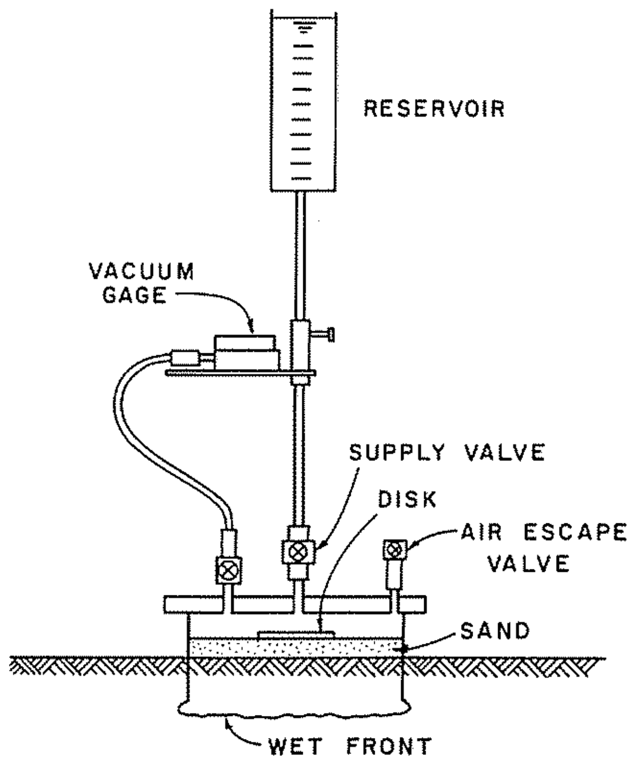

Fig. 4. Schematic of air-entry permeameter.

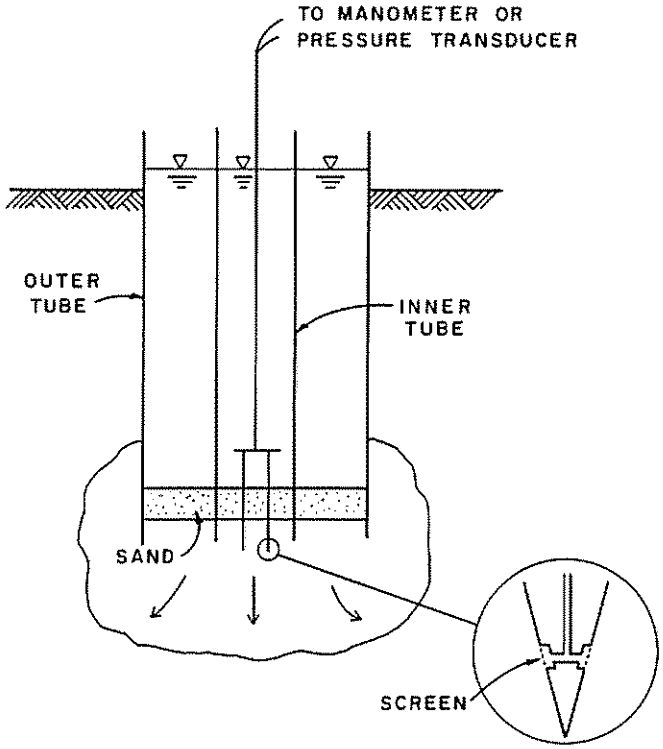

Fig. 5. Schematic of infiltration-gradient method.

permeameter is removed and the depth of the wetting front is measured, for example, by digging with a spade and observing how deep the soil was wetted. Knowing the depth of the water above the soil, the infiltration rate just before closing the valve, the depth of the wetting front at the time the valve was closed, and the pressure head at the wetting front while it was advancing downward, K in vertical direction of the wetted zone can be calculated with Darcy's equation. The method requires about 10 liters (3 gal) of water per test and is usually completed in less than 0.5 hour. In its present form of construction, the air-entry permeameter is a surface device. To use the device for measuring K at a certain depth, pits or trenches must be dug.

With the infiltration-gradient technique (Bouwer and Jackson, 1974, and references therein), an auger hole is dug and lined with a steel tube. A second steel tube of smaller diameter is placed concentrically in the hole and pushed or driven about 5 cm (2 inches) into the hole bottom (Figure 5). The tubes are filled with water and constant, equal, water levels are maintained in both tubes. Infiltration then creates a wetted zone with positive pressures in the soil below the auger hole. The infiltration rate from the inner tube is measured while small, fast-reacting piezometers are pushed into the auger-hole bottom at increments of about 2 cm (1 inch) to determine the vertical hydraulic gradient in the wetted zone. The K-value in vertical direction below the hole bottom then can be calculated with Darcy's equation. Once the hole is dug and the tubes are installed and filled with water, the test can usually be completed in about 1 hour, depending on K.

A third technique for measuring K in vadose zones is the double-tube method (Bouwer and Jackson, 1974, and references therein), which also consists of two concentric tubes in an auger hole with the inner tube penetrating the hole bottom about 2 cm (1 inch). The tubes are covered with a lid that has two standpipes—one connected to the inner tube and the other to the annular space between the inner and the outer tube in the hole (Figure 6). The tubes are filled with water and water levels are maintained at the top of the standpipes to create a wetted soil region with positive water pressures below the auger hole. When this region has reached sufficient size, the inflow into the inner tube is stopped and the fall of the water level in the inner-tube standpipe is measured. This is done while keeping the outer-tube standpipe full and, in another measurement, while adjusting the water level in the outer-tube

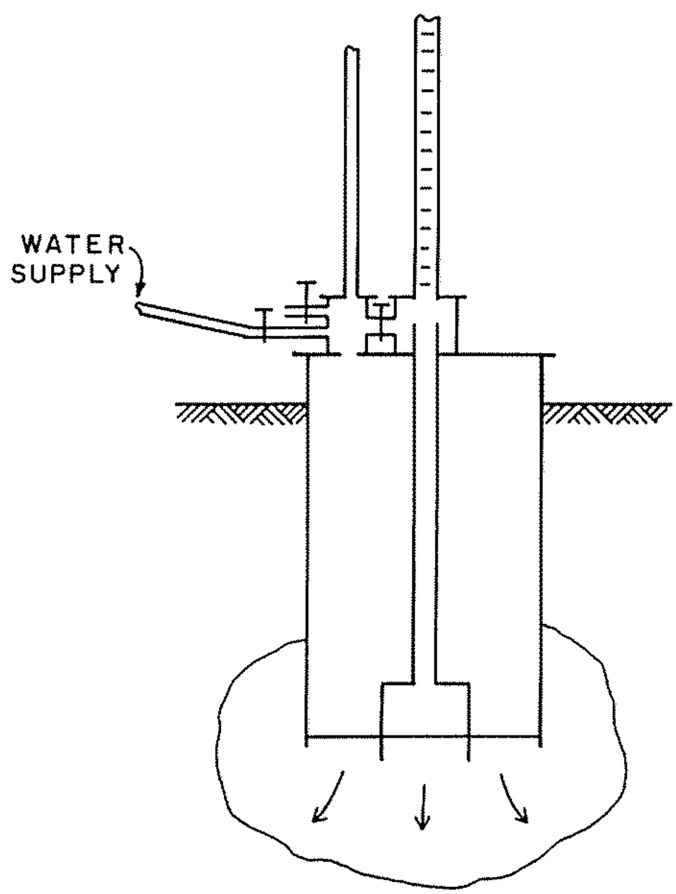

Fig. 6. Schematic of double-tube method.

standpipe so that it falls at the same rate as that in the inner tube. These measurements then yield the reduction in infiltration from the inner tube when the pressure head in the inner tube is less than that in the outer tube, which enables calculation of K of the wetted zone. The resulting value is affected by K in vertical and horizontal direction, but it mostly reflects K in vertical direction. The double-tube method requires about 2 to 5 hours to complete and about 100 liters (30 gal) of water per test.

Values of K in horizontal direction in the vadose zone can be determined with the shallow-well pump-in method. This technique consists of drilling an auger hole, filling it with water, and maintaining a certain water level in the hole until the outflow from the hole has become constant (Bouwer and Jackson, 1974, and references therein). Several days may be required before the outflow approaches a constant value and large quantities of water (hundreds of liters or about 100 gal) may be necessary. The value of K is calculated from the constant outflow rate and the hole geometry. The resulting value primarily reflects K in horizontal direction. A true measure of K in horizontal direction can be obtained by combining the double-tube method with the infiltration-gradient method in the same hole (Bouwer and Jackson, 1974, and references therein).

Where infiltration basins or other facilities are already available, like an experimental or pilot ground-water recharge system, the transmissivity, T, of the aquifer can also be determined from the measured rate of rise of the ground-water mound in response to infiltration (Bianchi and Muckel, 1970). This procedure yields the ratio T/f, where f is the fillable porosity. If f is known (f can be evaluated as the difference between the volumetric water contents above and below a rising ground-water mound), T can be calculated. When using this procedure, care should be taken in case T is measured from the mound rise below a narrow recharge strip and then used to predict the mound rise below a much wider strip or basin. This is because recharge flow systems in aquifers have an upper, active zone and a lower, passive zone if the height of the aquifer is larger than the width of the recharge basin (Bouwer, 1962). Thus, the effective transmissivity for a narrow recharge strip could be less than the actual transmissivity for the entire aquifer, and less than the effective transmissivity for a wider recharge strip. This would overestimate the height of a ground-water mound below a wide infiltration area if the height is based on T calculated from the observed mound rise below a narrow infiltration area.

CONCLUSION

Zoning aquifers for wastewater renovation is possible if the renovated water is discharged from the aquifer at some distance from the infiltration system. Successful application of the technique requires careful selection of the site, and careful design and operation of the system.

REFERENCES

Bianchi, W. C. and D. C. Muckel. 1970. Ground-water recharge hydrology. U.S. Dept. of Agric., Agric. Res. Service Publ. ARS 41-161, 62 pp.

Bouwer, Herman. 1962. Analyzing ground-water mounds by resistance network. Jour. Irrig. and Drain. Div. Amer. Soc. Civil Eng. v. 88, pp. 15-36.

Bouwer, Herman. 1970. Groundwater recharge design for renovating wastewater. Jour. Sanit. Eng. Div., Amer. Soc. Civil Eng. v. 96, pp. 59-74.

Bouwer, Herman. 1974. Design and operation of land treatment systems for minimum contamination of ground water. Ground Water. v. 12, pp. 140-147.

Bouwer, Herman and R. L. Chaney. 1974. Land treatment of wastewater. *In* Advances in Agronomy, N. C. Brady, ed., Academic Press, Inc., New York. v. 26, pp. 133-176.

Bouwer, Herman and R. D. Jackson. 1974. Determining soil properties. *In* Drainage for Agriculture. J. van Schilfgaarde, ed., Agron. Monograph, no. 17. Amer. Soc. of Agronomy, Madison, Wisconsin, pp. 611-672.

Bouwer, Herman and R. C. Rice. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Res. v. 12, pp. 423-428.

Cooper, H. H., Jr., J. D. Bredehoeft, and I. S. Papadopulos. 1967. Response of a finite-diameter well to an instantaneous charge of water. Water Resources Res. v. 3, pp. 263-269.

Gerba, C. P., C. Wallis, and J. L. Melnick. 1975. Fate of wastewater bacteria and viruses in soil. Jour. Irrig. and Drain. Div. Amer. Soc. Civil Eng. v. 101, pp. 157-174.

Hantush, M. S. 1967. Growth and decay of ground-water mounds in response to uniform percolation. Water Resources Res. v. 3, pp. 227-234.

Hunt, B. W. 1971. Vertical recharge of unconfined aquifer. Jour. Hydraul. Div. Amer. Soc. Civil Eng. v. 97, pp. 1017-1030.

Lance, J. C., F. D. Whisler, and R. C. Rice. 1976. Maximizing denitrification during soil filtration of sewage water. Jour. of Environ. Qual. v. 5, pp. 102-107.

Marino, M. A. 1974a. Growth and decay of groundwater mounds induced by percolation. Jour. of Hydrol. v. 22, pp. 295-301.

Marino, M. A. 1974b. Rise and decline of the water table induced by vertical recharge. Jour. of Hydrol. v. 23, pp. 289-298.

Singh, R. 1972. Mound geometry under recharge basins. Calif. State Univ., San Jose, Report No. GK-18526 for National Science Foundation, 71 pp.