MANAGEMENT OF ARTIFICIAL RECHARGE WELLS FOR GROUNDWATER QUALITY CONTROL[1]

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INTRODUCTION

An important application of artificial groundwater recharge techniques is for water quality control. Water spreading methods, for example, have been used for the tertiary treatment of sewage effluent [*McMichael and McKee*, 1966]. Although recharge wells are not generally used for sewage effluent management, such wells have been employed in various problems relating to chemical water quality. In Israel, where groundwater quality is a matter of national concern [*Aberbach and Sellinger*, 1967], recharge well techniques are used for the in-aquifer mixing of surface and groundwater supplies of dissimilar chemical quality.

As a result of theoretical, laboratory and field studies on underground mixing, the Israeli workers developed techniques to "predict and control the movement of water of various qualities...within the aquifers and in the water pumped for use" [*Harpaz et al.*, 1968]. The mixing theories and management techniques developed in Israel may have applicability to the solution of groundwater quality problems in Arizona. For example, high nitrate ion concentrations (>45 mg/l) have been reported in wells downstream of the outfall from the City of

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Tucson Treatment Plant. By importing low-level nitrate water to these high nitrate groundwater areas, coupled with in-aquifer mixing techniques it is possible that nitrate concentrations could be reduced to acceptable levels.

This paper briefly reviews specific recharge well-mixing techniques of possible utility in underground mixing operations for nitrate control. Illustrative data from field studies at a recharge site near Tucson, Arizona are presented.

EXPERIMENTAL

In-aquifer mixing may be effected by two possible well recharge regimes: the so-called single- and two-well types. A single-well operation comprises recharging effluent through and subsequently pumping the mixture of effluent and native groundwater from a single well. In a two-well operation, recharge is initiated in one well and pumping in a second well. Mixing is a reflection of several possible mechanisms: hydrodynamic dispersion, natural flow in the aquifer and stratified flow.

Single-well tests were conducted on a 20-inch diameter, 150 ft recharge well at the Water Resources Research Center (WRRC) field laboratory. Two-well tests utilized the 20-inch well in conjunction with a 260 ft distant 16-inch pumping well. Recharge effluent consisted of cooling-tower blowdown effluent from the nearby Tucson Gas & Electric Company, Grant Road Plant.

Differences in chloride ion levels were used to distinguish between (or label) recharge effluent and native groundwater.

Of several possible single-well techniques three were examined during field studies: the no-pause, pause and pulse types. The no-pause regime entailed recharging a volume of tagged, or labeled, recharge water followed immediately by pumping. During the pause regime a seven-day delay was interposed between recharging and pumping. For the pulse type regime separate volumes of tagged and untagged effluent were recharged sequentially, followed immediately by pumping.

A two-well test at the WRRC field laboratory comprised 14 days of continuous recharge-discharge in the two-well combination with matched recharge and discharge rates.

RESULTS AND DISCUSSION

Single-Well Tests

A representative chloride ion breakthrough curve for a no-pause, single-well test is shown on Figure 1. This curve was constructed by plotting the relative concentration of effluent in pumped water versus the corresponding pumped volume ratios, V_p/V_i; where V_p and V_i are the pumped and recharged volumes, respectively. The total volumes recharged and pumped during the specific test shown were 50,000 gallons and 181,000 gallons, respectively.

The breakthrough curve on Figure 1 illustrates the mixing trends during pumping. Undiluted effluent was discharged (i.e., relative concentration values remained near 100 percent) until a pumped volume ratio of about 0.4. With increased pumping more and more native groundwater moved to the well, mixing with and diluting the effluent and producing a decrease in relative concentration values. After extracting about 2.8 times the volume recharged the displacement of effluent was virtually complete and the relative concentration values approached zero.

Hydrodynamic dispersion was the principal mixing mechanism producing the curve of Figure 1. That is, the curve is S-shaped and relative concentration values approached the value predicted by dispersion theory: 50 percent for a pumped volume ratio of unity [*Harpaz et al.*, 1968]. For aquifers with high in-

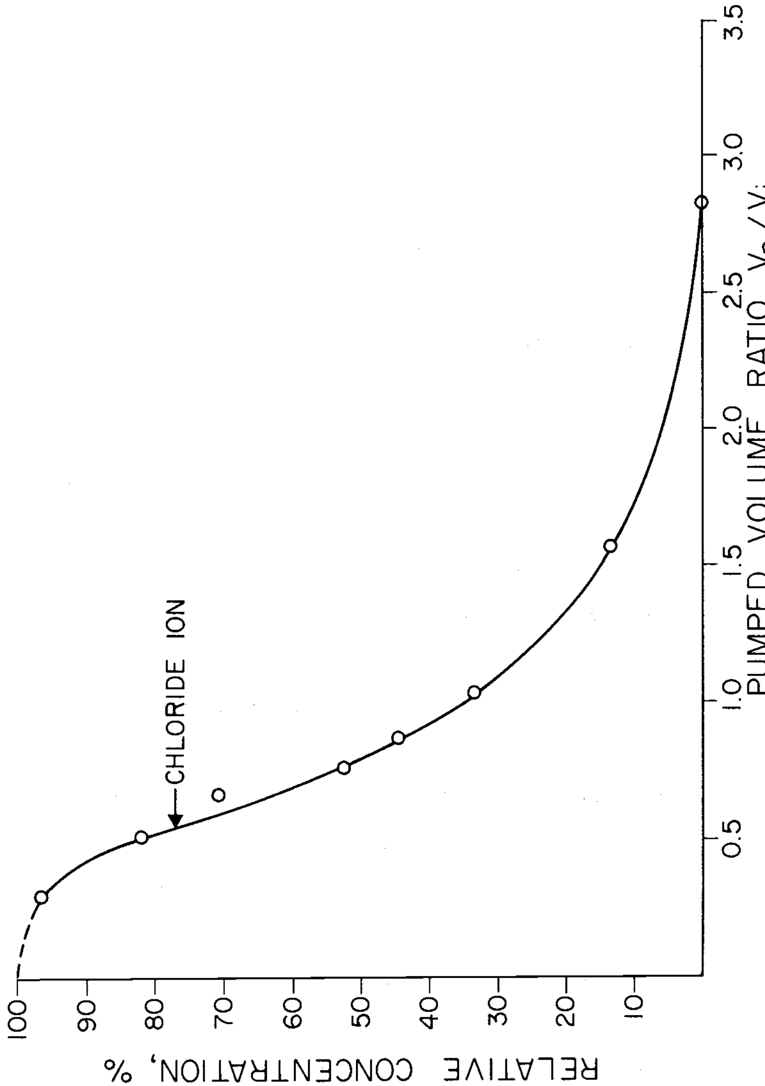

FIGURE I. BREAKTHROUGH CURVE SINGLE-WELL, NO PAUSE TEST digenous flow rates, such as the limestone aquifers in Israel, breakthrough curves are exponential in shape and relative concentration values are far less than 50 percent for pumped volume ratios of unity [*ibid.*]. Consequently, mixing is more effective when high groundwater velocities obtain.

Detailed results of a seven-day pause test were presented by *Wilson* [1971]. In general, by pausing between recharging and pumping more effective mixing was produced than by pumping without delay. After the seven-day pause the initial relative concentration values were about 20 percent [*ibid.*], c.f., 100 percent for the no-pause tests. Thereafter, relative concentration values for the pause case gradually approached zero.

The principal factor promoting dilution during the pause is probably indigenous groundwater movement which sweeps recharged water beyond the influence of the pumping unit. Other factors, listed by *Harpaz et al.* [ibid.], include percolation from above, density migration and molecular diffusion.

The results of pulse tests were also reported by *Wilson* [1971]. Relative concentration values on breakthrough curves for these tests were initially nearly zero, increasing to maximum values of about 25 percent for pumped volume ratios near 0.5, then decreasing thereafter. The initially low relative concentration values reflect the mixing of tagged and untagged effluent within aquifer materials. With continued pumping more and more tagged effluent was extracted but the low relative concentration values indicate that effective mixing of tagged and untagged effluent and native groundwater was occurring. After the maximal relative concentration values indigenous groundwater began to predominate in the extracted mixture.

Two-Well Test

A 14 day two-well test was conducted at the WRRC field laboratory using the 20-inch diameter recharge well and the downstream 16-inch pumping well. The constant recharge and pumping rates were matched at 200 gpm.

The chloride ion breakthrough curve at the pumping well is shown on Figure 2. An increase in relative concentration values was first evident on the fifth day. Values subsequently increased to 20 percent on the 11th day. A jog is evident on the curve between the 11th and 12th days, (possibly reflecting the effect of stratified flow) with an increase in relative concentration to 26 percent. This value was sustained to the end of the test.

The favorable dilution obtained during the two-well regime approached that during the pause-type, single-well regime. The principal advantage of the two-well regime over the single-well regime would be for the treatment of effluent or groundwater on a prolonged or continuous basis. *DaCosta and Bennett* [1960] indicated that effectiveness of the two-well regime may be increased by the judicious selection of recharge-discharge rates, by increasing the distance between the recharge-discharge wells and by aligning the wells at certain angles to the direction of indigenous flow.

Applicability of Mixing Techniques to Nitrate Dilution

Chloride ion breakthrough curves such as those shown herein illustrate the possible mixing trends during single- or two-well operations for nitrate control. Thus if the nitrate ion concentrations of the recharge source and groundwater are known for a specific site and empirical chloride ion breakthrough curves are available for various recharge-discharge regimes, the dilution principle may be used to estimate changes in nitrate ion concentrations during underground mixing.

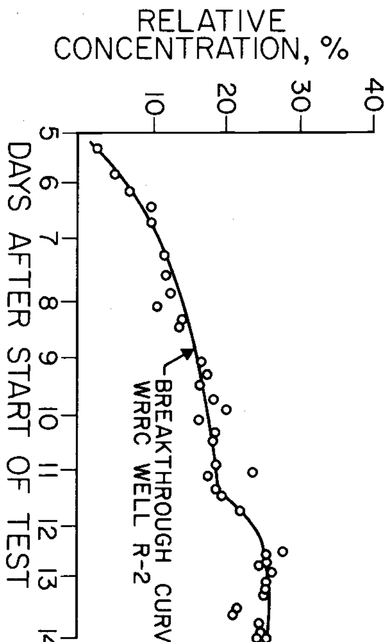

FIGURE 2. CHLORIDE ION BREAKTHROUGH CURVE, WELL DURING TWO-WELL, RECHARGE-DISCHARGE TEST

The most efficacious system for the quantity and quality of dilution water may then be selected for the site.

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