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MICROSCALE CHEMICAL HETEROGENEITY IN GROUNDWATER

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ABSTRACT

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Large variations in the concentration of Cl^- , NO_3^- and SO_4^{2-} in the upper water layers of a polluted aquifer were found between samples that were vertically separated by as little as 3 cm. This was disclosed when a multilayer dialysis cell device was used to obtain undisturbed, real-time samples from test wells. This first time presentation of chemical fine structure provides new insights into mechanisms of contamination of an aquifer by surface inputs and raises the question of the validity of groundwater quality data based on single samples, however obtained.

INTRODUCTION

The understanding of transport phenomena of pollutants in the water of an aquifer requires detailed real-time knowledge of the distribution of chemical species with a high spatial resolution. Such data have been unavailable until the recent development of a sampling probe with a vertical resolution of 3 cm (Ronen et al., 1986a). This technique has permitted the investigation of the chemical fine structure of groundwater and has been applied to the study of the water table region of a polluted aquifer that underlies a cultivated field (Ronen and Magaritz, 1985).

The study has produced a picture of complexity and variability in chemical quality at the microscale level. When the many variables of quantity, quality and periodicity of the input waters, as well as the multidimensional flow, are considered, variations in water quality at a single sampling site are to be expected. The findings reported herein are unique in: (1) the range of variations of three common measures of chemical quality between microscale (0.01–1 m)

slugs or parcels* of water; and (2) the sharpness of the boundaries between these parcels.

Site description

The reported study was conducted in a cultivated field, 15 km north of Tel Aviv and 2 km inland from the Mediterranean Sea. The field overlies a portion of Israel's Coastal Plain Aquifer. This aquifer stretches along 120 km from Mount Carmel to the Gaza Strip; its width varies between 7 and 20 km. It has a wedgelike cross section with a maximum thickness of 180 m near the sea that tapers towards the east where it disappears near the foothills of the Samarian and Judean mountains.

The aquifer is composed of clastic sediments of Pleistocene age overlying impervious clays of Pliocene age. The Pleistocene sequence consists of inter-fingered continental and marine units composed of sandstone, calcareous sandstone, siltstone, and red loamy soils (Issar, 1968). In the eastern half, the aquifer is uniform and phreatic. Towards the west, it is partially divided by intervening clay layers into subaquifers of which the lower ones are confined. Mercado et al. (1975) estimate that the aquifer stores $21 \times 10^9 \text{ m}^3$ with $0.4 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ extracted by pumping through 1600 wells. The aquifer is replenished by an annual rainfall of approximately 500 mm that falls only in the winter months. Since 1963, there has been additional artificial replenishment throughout the aquifer with surface waters originating in the Sea of Galilee.

At the study site, municipal sewage that has been treated by various processes has been used for irrigation for the past 20 yr. The two test wells are located 400 m apart west of an inland depression of the water table surface caused by overpumping (Fig. 1). The water table is 30 m below the surface and the aquifer is 130 m thick. The horizontal specific discharge of the groundwater at the water table region was measured by a modified single-well dilution technique using ^{18}O depleted water as a tracer (Ronen et al., 1986b). It was determined to be 0.5 m year^{-1} in the upper half meter of the saturated zone and 4 m year^{-1} below this level. If a 40% specific porosity is assumed for the homogeneous sandy profile the lateral movement of water is 11 cm month^{-1} and 83 cm month^{-1} , respectively.

METHODOLOGY

The samples for this study were collected with a 5 cm diameter rod that contained over a length of 240 cm, 76 dialysis cells exposed to the water in the well screen (Ronen et al., 1986a). In such a system, 99% equilibrium has been shown to occur in a 48 h period for Cl^- and NO_3^- while SO_4^{2-} took about twice this time. The contents of the dialysis cells were analyzed by ion chromatography with a variance below 4%.

*The "parcel", a subjective concept, is that volume of groundwater that appears by the tests performed by the investigator to be homogeneous.

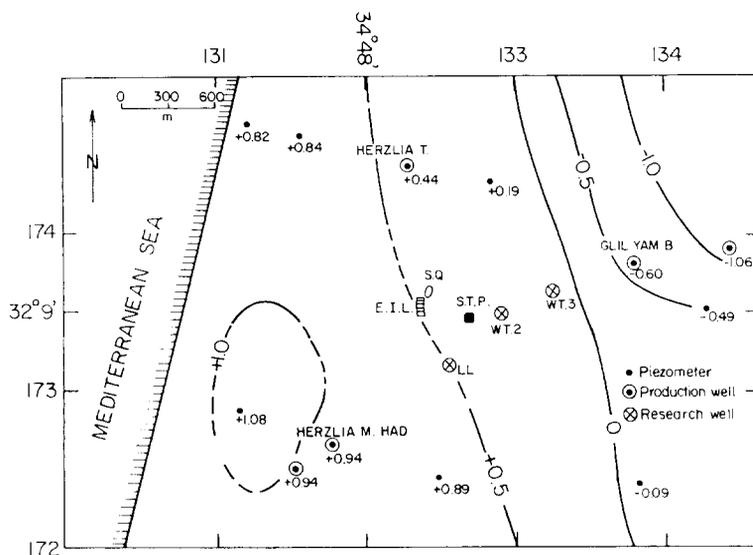


Fig. 1. Regional map showing the location of the pumping and research wells, sewage treatment plant (S.T.P.), effluent infiltration lagoons (E.I.L.) and sludge disposal site (S.Q.). The elevation of the groundwater table above sea level is also shown.

RESULTS

The results of two chemical profiles observed 42 days apart are presented in Fig. 2. The complexity as well as the microscale of chemical inhomogeneity has, in our opinion, been clearly demonstrated. In a single test sampling (profile A in Fig. 2) over a vertical range of 240 cm, the Cl^- varied from 160 to 270 mg l^{-1} ; NO_3^- , from 0 to 110 mg l^{-1} ; and SO_4^{2-} , from 45 to 70 mg l^{-1} . When the same well was examined 42 days later (profile B) an entirely different pattern was found. For example, between 60 to 160 cm depth, the Cl^- and NO_3^- concentration decreased by as much as 120 and 60 mg l^{-1} , respectively. When results of six successive sampling profiles are presented in a three-dimensional array as seen in Fig. 3, the microscale inhomogeneity is further confirmed as the time scale is, in some manner, related to horizontal flow. The results obtained by sampling the second research well show a similar pattern of complexity.

DISCUSSION

The vertical dimensions of the water parcels of different chemical composition range from tens of cm to about one meter. Their horizontal dimension, estimated from the flow rates, is in the order of one meter. These parcels reflect the infiltration of discrete water layers of different chemical composition detected in the unsaturated zone (Gvirtzman et al., 1986). The origin of these layers is the intermittent input of rain and irrigation water (sewage effluents) on the replenishment area of the aquifer. The absence of nitrate between 30 to 55 cm depth, in both profiles, is assumed to be the consequence of denitrifica-

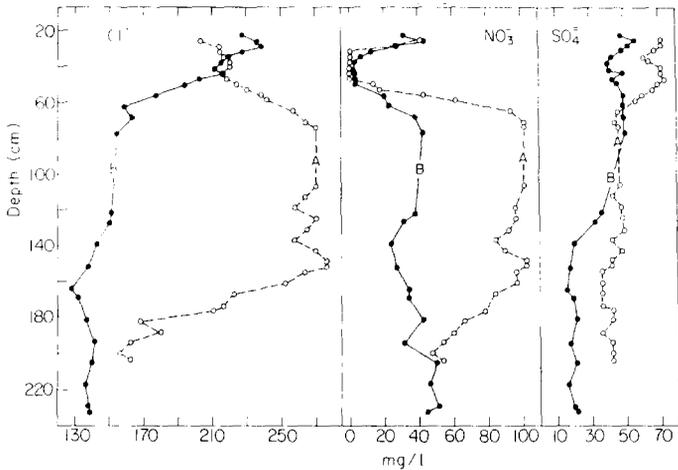


Fig. 2. Cl^- , NO_3^- and SO_4^{2-} profiles in the water table region of research well WT-3 in the Coastal Plain aquifer of Israel. Profiles A (dashed line) and B (solid line) were sampled April 28 and June 10, 1985, respectively. During this period the water table rose by 3 cm. The depth of each sample was calculated from a fixed reference level. The first data point in each profile shows the concentration of solutes in the first 3 cm below the water table.

tion (Trudell et al., 1986) in a region where groundwater is almost stagnant.

It is certain that these disclosures will irritate the hydrologic scientist's desire to carry his research beyond phenomenology and into the realm of predictive theory. This demonstration of microscale chemical inhomogeneity, albeit in a heavily exploited aquifer, must make us suspect of temporal and spacial inhomogeneity in all groundwater flow patterns.

What is the time frame of integrity of the parcels? The sharp change that is seen in both line (A) and line (B) of Fig. 2 that depict Cl^- concentrations suggests some type of boundary between parcels that prevents equilibrium. In time, the boundary between parcels must disappear because of molecular diffusion, mechanical dispersion and possibly gravity flow. Calculations with available diffusion constants for Cl^- indicate that steady-state equilibration would produce a homogeneous zone with a width no greater than 6 cm within the 42 day period between samplings. Although in the present study we analyzed only Cl^- , NO_3^- and SO_4^{2-} we expect that other ionic species will show similar heterogenic patterns. We are currently investigating the deeper layers of the aquifer described herein as well as desert aquifers that contain mainly paleowaters with the view to better understanding this phenomenon of parcelization.

We believe that microscale heterogeneity at the water table region will be found in most polluted aquifers. Studies on the variability of the chemistry of water supplied by individual pumping wells (Schmidt, 1977; Ronen and Kanfi, 1981), as well as mesoscale (0.1–1 km spacing) samplings of pumping fields (Eccles and Bradford, 1977) provide supporting evidence on the existence of larger parcels of water of different quality in groundwater.

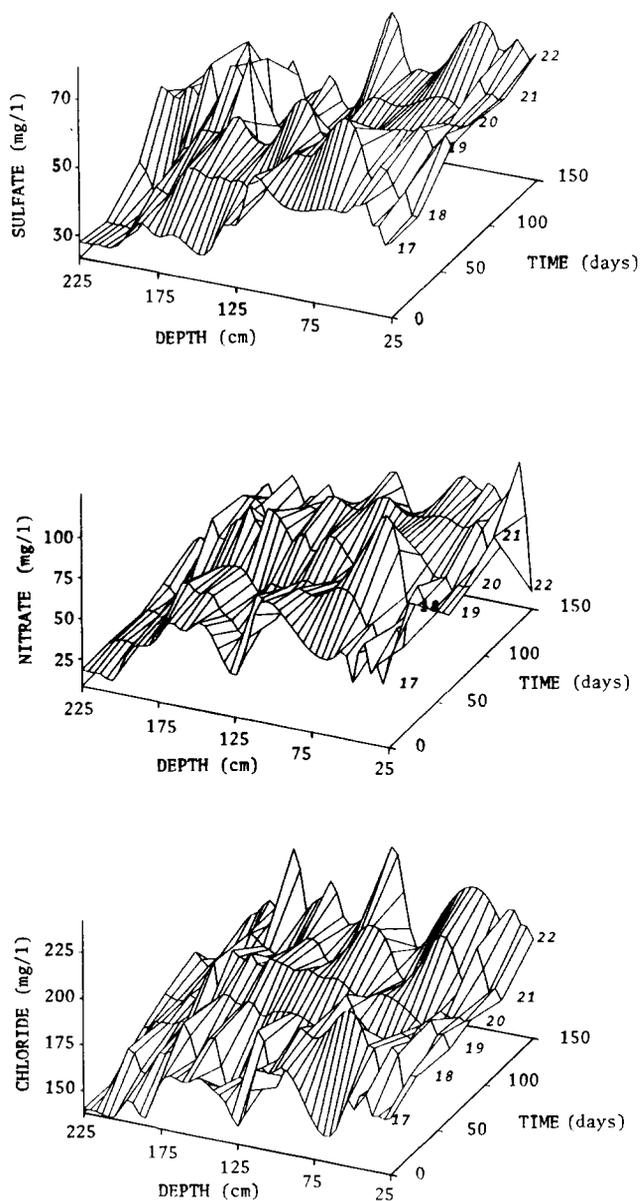


Fig. 3. Three-dimensional representation of Cl^- , NO_3^- and SO_4^{2-} profiles in the water table region of research well WT-3 in the Coastal Plain aquifer of Israel. Profiles 17 to 22 were sampled from the 11 May to 13 October 1985.

There are practical implications to the recognition of microscale inhomogeneity. For example, if the waters indicated by the lines (A) in Fig. 2 were intended for water supply, they would be unsatisfactory for irrigation of citrus and avocado because of high Cl^- and unsatisfactory for drinking water because

of the high level of NO_3^- . In contrast, waters indicated by the lines (B) are quite satisfactory for both purposes. Until the volume, the chemical concentration and the time period of stability of parcels are established, we can have little confidence in the analysis of chemical water quality of samples withdrawn from active pumping wells.

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