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PERMEABILITY DECREASE IN COASTAL AQUIFERS DUE TO WATER-ROCK INTERACTION

SUMMARY

Seawater and fresh groundwater were made to flow through columns filled with sediments from a «good aquifer» that contain 5% or less clay-minerals.

Hydraulic conductivity (H.C.) decreased very sharply whenever seawater was flushed by fresh groundwater. The extend of the decrease reached 10^{-1} to 10^{-3} of the original H.C.. Subsequent flushing with seawater restored H.C. only slightly, if at all.

Similar results were obtained when using artificial mixtures of analytically pure sand and montmorillonite. But, illite-sand and kaolinite-sand mixtures were not influenced by the type of the water.

The model that explains the H.C. decrease is based on the formation of waterclay gel configurations that behave as practically rigid particles and clog the bottlenecks between adjacent pores.

Examination of the hydrological situation of parts of the Israel's Coastal Aquifer yields results similar to these obtained in the laboratory.

1. INTRODUCTION

Hydrological processes characterizing sandy coastal aquifers are the subject of research of this paper. The role of the water-rock interaction in those

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processes is emphasized, related to the behaviour of very minute amounts of clay minerals in a seawater-fresh ground water interface environment.

The analysis, simulation and management of coastal aquifers are usually based on two assumptions: *a*) Aquifer parameters, especially hydraulic conductivity (H.C.), remain constant throughout the time-span under consideration, and *b*) the seawater-freshwater interface is a movable boundary, modified by the effects of diffusion and hydrodynamic dispersion (BACHMAT and CHETBOUN, [1], KAPULER [6], MERCER and FAUST [8], VOLKER et al. [10]).

However, observations in the Israeli Coastal Aquifer contradict these assumptions, and models based on them appear to be inaccurate. Expected intrusion of seawater over extensive areas near the coastal line, where depressions appeared due to intensive pumpage, are generally not monitored. At any rate, it is certain that this intrusion is by far not as massive as predicted.

This paper is focussed on the properties of the interface system, and contributes to elucidation of this apparent contradiction. Laboratory experiments were conducted to find out the role of different components of this aquifer zone.

The experimental results indicate that, in sandy coastal aquifers containing a minute amount of montmorillonite, the water-rock interaction may cause a rapid and very drastic decrease of hydraulic conductivity. In extreme cases such amounts of clay may transform the assumed movable boundary between seawater and freshwater into a practically fixed one.

2. MATERIALS AND METHODS

The sediments tested were uncontaminated samples taken from research boreholes in Israel's Coastal Aquifer near Ashdod and near Askelon, wave-washed sands, dune-sand (situated 4000 m inland), and pure quartz sand (supplied by B.D.H.). The samples were characterized by grain-size-analysis, X-ray analysis for mineralogic composition, permeability and porosity.

The waters used were Mediterranean seawater, water from the Ashod aquifer (Tab. 1), as well as various mixtures of $CaCl_2$ and NaCl solutions of different ionic strenght.

TABLE 1 - Chemical analysis of water (in meq/1).

	Na^+	K^+	Ca^{+2}	Mg^{+2}	Cl^-	HCO_3^-	SO_4^{-2}	E.C. (μmho/cm)
Aquifer water from Ashdod (1)	3.8	0.1	2.6	2.0	4.6	3.4	0.4	780
Mediterranean seawater (2)	530.0	11.0	22.8	107.3	615.0	2.2	60.0	48.500

(1) Analyses done in the chemical laboratory, Israel Geological Survey, at author's request.
(2) Nadler et al (1980).

The dispersion of clays was demonstrated by a series of microphotographs. Natural sediments, as well as artificial mixtures of sand and clay were examined for the effects caused by the passage of various types of fluid, by using a petrographic microscope, equipped with a camera.

The experimental set-up consisted of: 1) columns equipped with electrodes, which allowed monitoring of the electrical conductivity of the system within; 2) calibrated vessels, for introducing and collecting the influent and the effluent.

Small modifications of the experimental set-up were made in the course of the experiments. (Goldenberg et al. [3]).

3. SUMMARY OF EXPERIMENTS AND FIELD OBSERVATIONS

I. A series of experiments with sediments from the Israeli Coastal Aquifer and with artificial mixtures of pure sand and clay reveal that aquifers stay «good» when seawater, or fresh ground water, flows through alone. But, when the type of water changes, the permeability decreases, arriving in some experiments at value of one-tenth, in others at onethousandth, or even less, relative to their original value (Tab. 2 and Fig. 1). During these experiments, in some cases when displacement of saline water by fresh water took place, a cyclic behaviour of H.C. and E.C. was observed. It appeared as an increase in

Table 2 – Darcy's K-coefficients range of values.

Sample Identification	K-coefficient value	
	maximum value cm/sec	minimum value cm/sec
Zikim N116 6.0 - 6.45m	$1.63 \cdot 10^{-2}$	$3.33 \cdot 10^{-5}$
Zikim N116 12.0 - 12.45m	$3.30 \cdot 10^{-3}$	$1.17 \cdot 10^{-4}$
Zikim N113 13.5 - 13.95m	$4.83 \cdot 10^{-3}$	$4.80 \cdot 10^{-4}$
Zikim N116 36.0 - 36.45m	$3.77 \cdot 10^{-3}$	$1.36 \cdot 10^{-4}$
Zikim N116 48.0 - 48.26m	$1.84 \cdot 10^{-3}$	$2.1 \cdot 10^{-4}$
Wadi Soreq Sand	$1.78 \cdot 10^{-3}$	$1.16 \cdot 10^{-6}$

the E.C. values in the columns, which was closely followed by an increase of the H.C. (Goldenberg et al. [3]). Introduction of a dilute NaCl solution into the sediment rapidly reduced the H.C. by about 3 orders of magnitude (Fig. 1, B).

II. The matrix components of the aquifer were analyzed in order to establish which of them is responsible for the H.C. decrease phenomenon. Experiments conducted on various sediments certainly point to the clay fraction as being the responsible one (Goldenberg et al. [4]). Studies conducted with different types of clay mineral (kaoline, illite and montmorillonite) show the following results:

a) 1.5% of montmorillonite in the mixture allows an undisturbed seawater flow. Above this amount, the influence of this type of clay on the H.C. is (Fig. 2):

$$K = KO*\exp\ (-0.85*C)\quad (\text{eq. } 1)$$

(R : log K:C=−0.98 [.0063]).

K = hydraulic conductivity (cm/sec).

C = % of clay in the mixture.

R = coefficient of linear regression.

KO = value of K when C=O found by linear extrapolation.

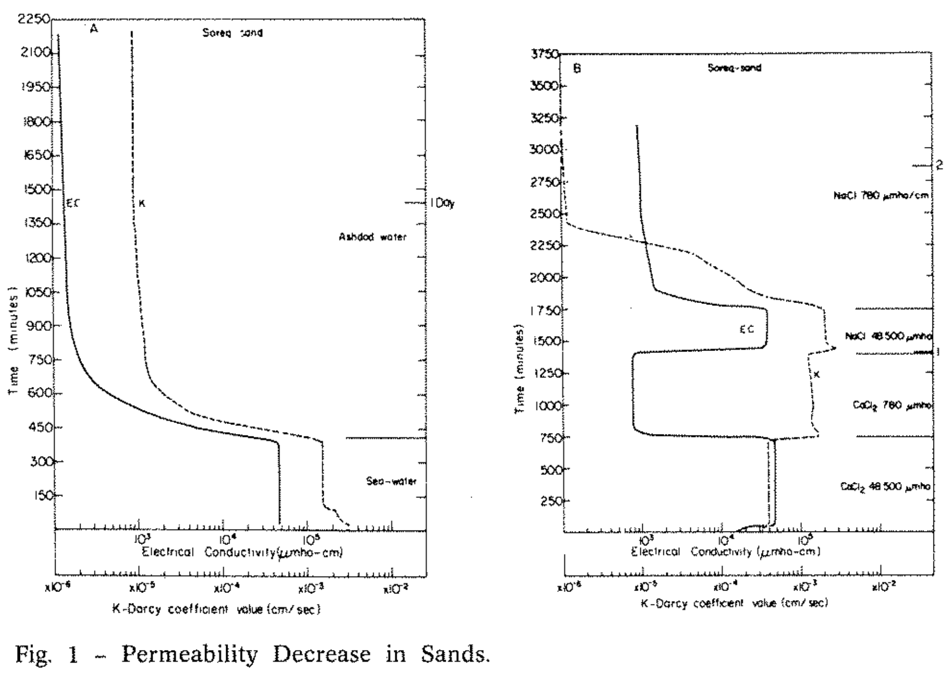

Fig. 1 – Permeability Decrease in Sands.

b) The H.C. decrease is influenced by illite and kaolinite in sand mixtures to an extent of about one half of that of the montmorillonite:

$$K = KO*\exp(-0.43*C) \quad \text{(eq. 2)}$$

c) When flushing the seawater by fresh ground water the system became activated and, the H.C. of the sand-montmorillonite mixtures drastically decreased. This was observed also in natural sediments collected from the coastal aquifer. When 3% and 7.5% of clay were present, the H.C. decreased drastically, to 10^{-6} and 10^{-7} cm/sec. respectively. The second value is approximately the experimentally detectable limit. The relation between the clay content and the H.C. value is:

$$K = KO*\exp(-3.036*C) \quad \text{(eq. 3)}$$

(R : log K:C = – 0.949)

IV. 1) The shoreward movement of saline water was examined in the Israeli Coastal Aquifer.

The analyses show: water levels were depressed below sealevel over extensive areas near the coast for long periods, but seawater intrusion became a problem only in Tel-Aviv region (hydrological strips 29-32); there, depressions of 4 to 11 m below sealevel, at 2 km distance from the shore, were created for a period of 10-15 years (Fig. 3). Some minor intrusions only were proved also in the Emeq Hefer area.

2) In order to push the interface seawards by creating hydrostatic pressure of high quality water against the saline water, the pumpage in this zone

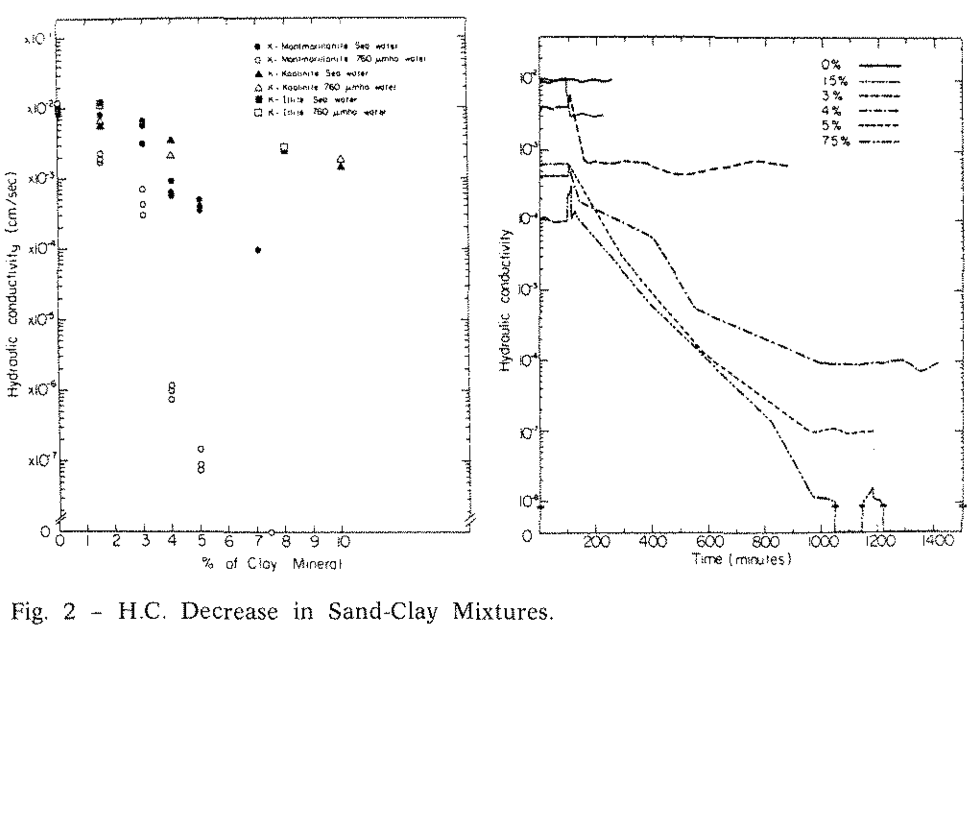

Fig. 2 - H.C. Decrease in Sand-Clay Mixtures.

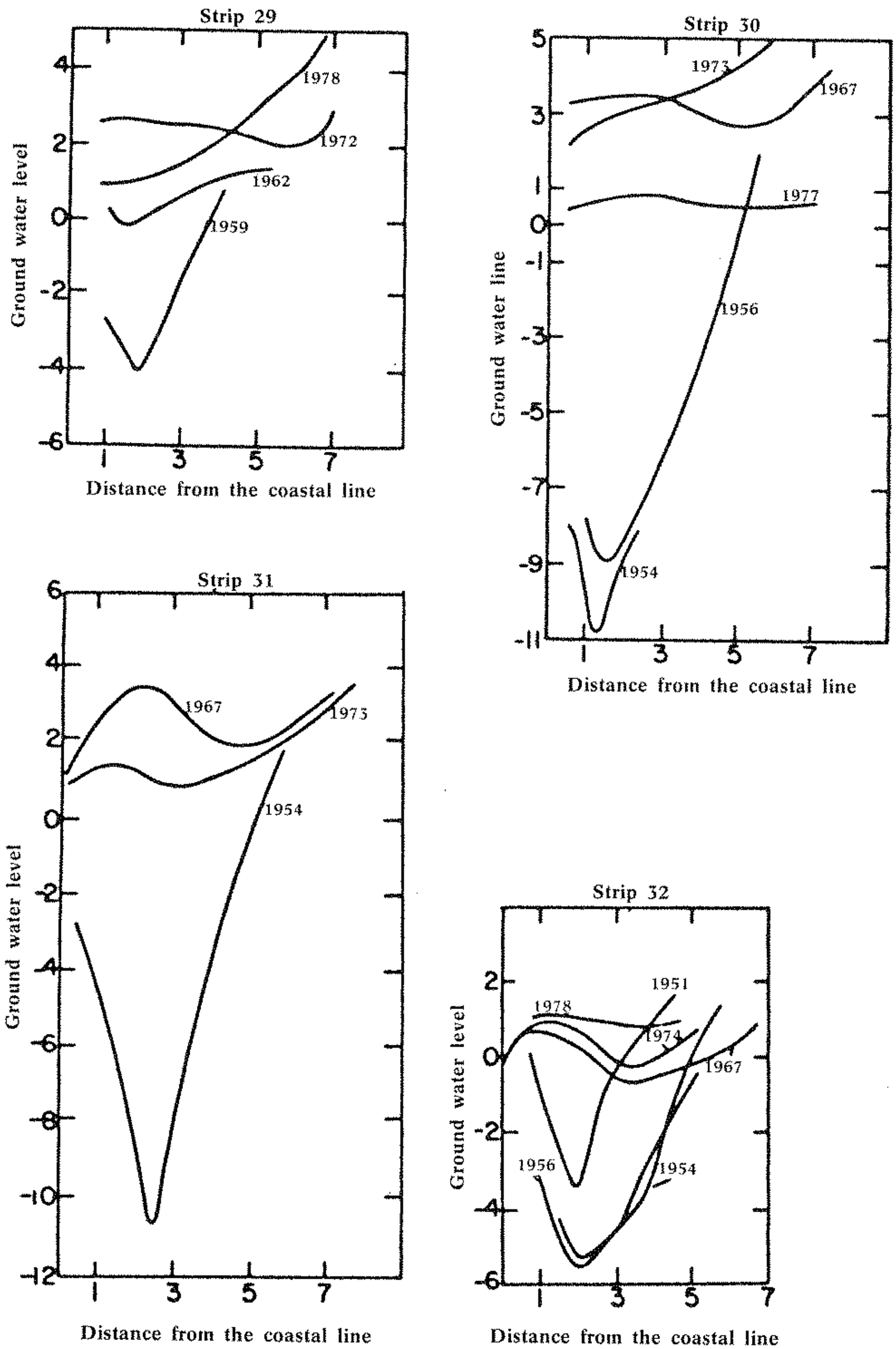

Fig. 3 - Hydrological Situation in Tel-Aviv Region.

was drastically reduced, or even totally stopped, fresh groundwater has been introduced, but the T.D.S. content of the water in this zone is still high-about 500-2000 mg-Cl/1, as in the last period of intensive exploitation.

3) Introduction of high quality water in seawater-contaminated wells resulted in rapid head development, without a large quantity of water entering into the aquifer.

V. Micro-photographs of sediments in contact with seawater and freshwater consecutively, clearly show that a thin coating of clay on sand and intragranular clay packets expand to a large size.

VI. Dolomite formation is an other aspect of the water-rock interaction in the interface zone. Using a scanning electron microscope and x-ray diffractometer, horizons of protodolomite were detected, coinciding with interface zones of different ages. It was found that protodolomite crystals, reaching a size up to 50 um, were created in voids between the previously existing grains (MAGARITZ et al., [7]). This continuous process of dolomite precipitation in the diffusion zone might have also some effect on the decrease of permeability of coastal aquifers by reducing their pore space.

4. DISCUSSION

1) The relevant processes are summarized in Fig. 4.

In stage 1 only one kind of water flows through channels formed by pores of varying size, the clay fraction is in a flocculated state and forms more or less dense packets that coat the grains of the sediment and fill a small part of the pore space. If freshwater flows through the pores flocculation is maintained by the prevalence of Ca ions. If seawater flows through the pores flocculation is maintained by the high ionic strenght. In either case the system remains in a stable, unactivated state.

In stage 2 the type of water is changed and the system becomes activated. If the saline water is displaced by fresh ground water a dilution occurs, arriv-

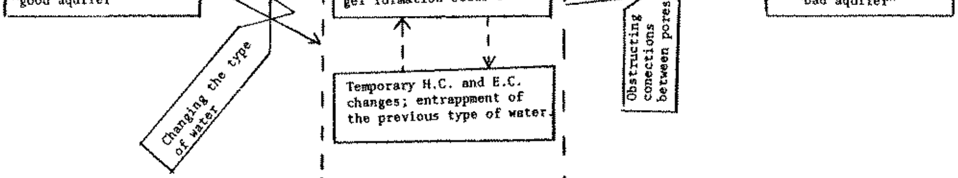

Fig. 4 – The conceptual approach.

ing at a treshold value at which the clay fraction is induced towards deflocculation. The clay becomes very reactive, and is partly transformed into small gel-droplets with a certain resistance to shearing stress. They float with the flowing water until they become lodget in bottlenecks between pores.

As a consequence H.C. of the sediment quickly decreases by a factor of 10^{-4} to 10^{-5}. The system may be said to be in an unstable activated state.

In this stage a cyclic flow behaviour appears under certain conditions, related to the H.C. and E.C. behaviour. Because of different flow-velocities, inclusions of the previous type of water are formed. Along their borders gel-walls are sometimes formed, and they dissapear under certain conditions.

In state 3 connections between pores are, to a large extent, blocked, and permeability has decreased to a very small value. This condition is being characterized by a large «resistence» to changes. This fact means that the process is a practically irreversible one. Even if seawater is made to flow through the pores its interaction with gel-droplets proceeds at a very slow rate due to the blocking of passages. The system may be said to be in an activated stable state.

2) One may use the C-factor which appears in the equation given by Davis and deWiest [2] for the hydraulic conductivity coefficient (K) in the Darcy's law to explain both the field and laboratory results. Hydraulic conductivity (H.C.) can be expressed, by dimensional reasoning, as:

$$K = C * d^2 * \gamma / \mu \quad \text{(eq. 4)}$$

where C is a nondimensional parameter characterizing connectivity, d^2 is the representative cross-section area of an average pore, γ and μ are specific weight and dynamic viscosity of water, respectively. (In many texbooks d is defined as «average grain size» and C is assumed to refer to a packing parameter as well as to connectivity. The above definition is better suited to our present purpose).

One may argue that the process described above can be interpreted as leading to the reduction of the factor C, (connectivity).

5. CONCLUSIONS

a) The seawater-freshwater interface in a coastal aquifer necessarily shifts on a quasi-geologic time scale due to climatic changes and eustatic changes of the sea-level. In an aquifer containing 3% or more montmorillonite these shifts create a zone of strongly reduced permeability that impedes subsequent shifts of the interface.

An additional fact that acts in the same direction is the existence of a certain amount of suspended matter in the seaward flowing groundwater. The inorganic fraction of this matter arrives at the interface zone almost in an activated form of pre-gel-droplets, contributing to the lowering of the H.C. value. A simulation that ignores this almost impermeable boundary necessarily yields wrong predictions.

b) Attempts to push the interface seaward by artificial recharge of freshwater are likely to clog the aquifer. According to accepted theory, the saline water front is believed to be pushed seawards, the reality is quite different. Thus, such attempts to push the interface seaward by injection of fresh water in the zone of mixing defeat their own purpose.

c) An interesting scientific ramification concerns the possible transport of freshwater across the interface zone into sea: it may be assumed that along portions of a seawater-fresh ground water zone the droplets of gel in the pore-space form a semipermeable membrane. This may cause an equilibrium state between the output of fresh water and the head in the two sides of the interface. Quantities of fresh-water may be transfered to the sea due to osmotic pressure. The inverse situation may also occur in certain conditions, and quantities of «distilled water» may enter into the freshwater part of the aquifer after «desalinization». However, at present, these are only hypotheses.

The above mentioned finding may have a great hydrological importance. It may be inferred that fundamental laws regarding the behaviour of aquifers in the interface zone, such as the Ghyben-Herzberg rule, may not be valid, or valid with some modifications. If the passage of fresh water to the sea may be modified by such processes as small movements of the interface are, one is led to believe that many aquifers may be obstructed in a larger or a smaller measure due to it. Thus, one may state that the interface region behaves as a «bottleneck» of the aquifer system.

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