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EVALUATION OF GROUNDWATER SALINITY FROM WELL LOGS AND CONCLUSIONS ON FLOW OF HIGLY SALINE WATER

SUMMARY

Groundwater conductivity was evaluated from resistivity - and porosity logs applying the formation factor concept. From the conductivity the density of highly saline waters with a main content of sodium chloride was calculated. These data were used in combination with density data from water samples to derive the three-dimensional density distribution in the sedimentary cover of a salt dome. An aquifer directly on top of the salt dome exhibited nearly plane surfaces of equal density. From the vertical density gradient and the inclination of these planes the relative change of the Darcy-velocity in relation to the depth was evaluated.

During an investigation of fresh and saline groundwater flow in unconsolidated sediments we had to deal with two problems:

– First, to calculate continuous profiles of groundwater conductivity and density from borehole measurements,

– second, to apply the density data to the evaluation of groundwater flow.

In the region of the study the saline water originates from the solution of salt at a salt dome. So water of very different salt content, ranging from fresh water to saturated salt solution, is found.

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In this case the density differences are, of course, extreme, but the methods used may be applied to coastal aquifers in a similar way.

The sediments of the investigated area consist of sands, clays, and silts, of mainly quaternary age and mainly glacial or glaciofluvial origin.

The available data were: a pumped water sample and water level data from each observation well and the following well logs: Gamma Ray Log, Focussed Electric Log, Induction Electric Log, Spontaneous Potential Density Log, and Caliper Log.

We tried to derive continuous profiles of groundwater conductivity by evaluating the formation resistivity from the Focussed Electric Log or the Induction Log and calculating the water resistivity by use of formation factors.

For the determination of formation factors we first tested the applicability of the Archie formula.

Testing is possible at points, where water samples are available. Fig 1 shows a plot of the formation factor versus the porosity of the formation. The formation factor values were calculated by dividing the formation resistivity R_o by the water resistivity R_w of samples.

The data were restricted to water samples of low restivity. Only in this case is the quotient R_o/R_w equal to the true formation factor.

The porosity was evaluated from the Density Log data. The points are scattered around the drawn curve, which represents the Archie relation after inserting the Humble coefficient and exponent [1].

There are considerable deviations from the curve, but the application of the formula will obviously provide better results than the assumption of a constant formation factor.

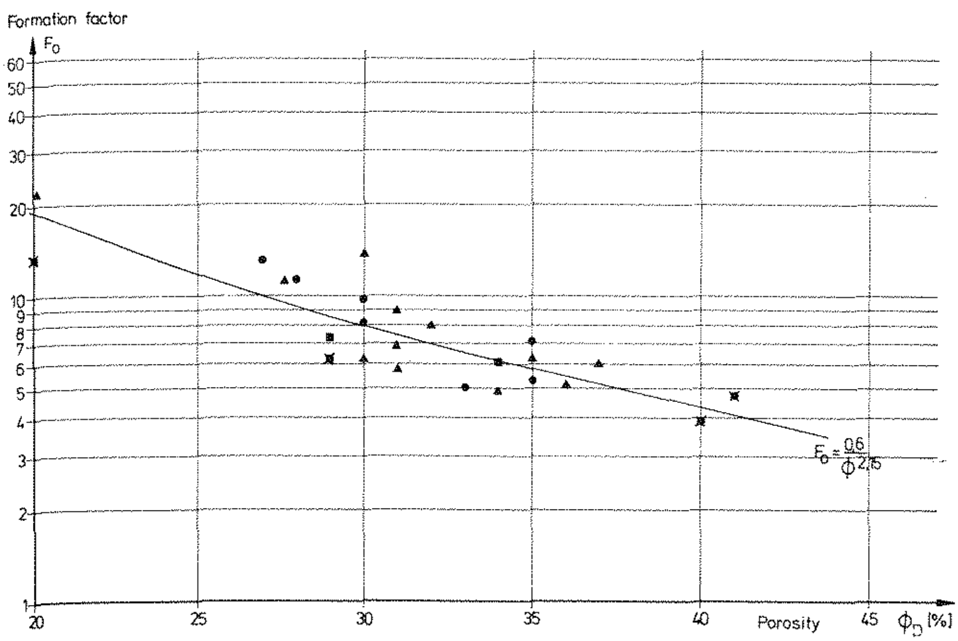


Fig. 1 - Formation factor versus porosity. The data refer to quaternary sands of glacial origin.

Consequently the application of the Archie-Humble relation, which was derived primarily for oil field formations, to unconsolidated quaternary sediments is justified, as long as there is no better method.

In groundwater with large variations of salinity the difference between true and apparent formation factors has also to be taken into account [2].

The apparent formation factor F_a is defined as the quotient R_0/R_w, while the true formation factor F_0 is the limit of R_0/R_w for R_w approaching zero.

Fig. 2 shows the apparent formation factor F_a in relation to the water resistivity R_w. These are data of sand aquifers of the investigated area. The water resistivities are measured values of pumped water samples.

F_a decreases with increasing water resistivity. This is an effect described by different authors [2,3], with respect to laboratory and field measurements of sand resistivities.

It may be explained as follows: The conductivity is made up of two parts: one which is proportional to the conductivity of the electrolyte, and one which is independent of the conductivity of the electrolyte. The latter one results from ionizing forces at the pore surfaces. We call the corresponding resistivity R_i – the resistivity related to the internal surface of the porous material. R_i is big for coarse and clean sands, and it is small for silt and clay.

So we have two characteristic values for a formation, defining its resistivity in relation to water resistivity: the true formation factor F_0 and the internal-surface resistivity R_i.

While F_0 may be approximately calculated from well log data, as mentioned above, only average R_i values for certain regions or formations may be

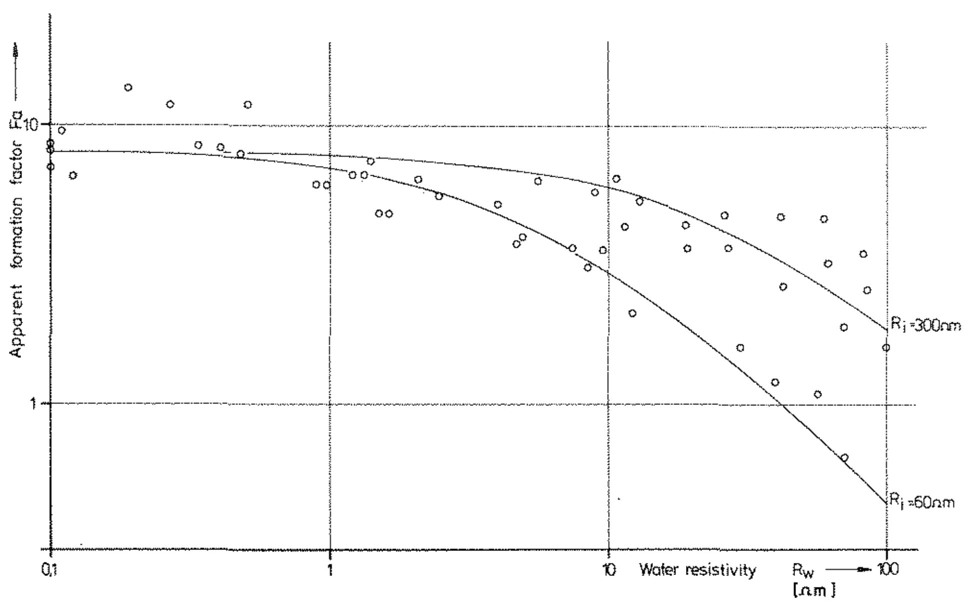


Fig. 2 – Apparent formation factor in relation to water resistivity. The data refer to quaternary sands of glacial origin and varying silt content.

estimated. So, for instance, the two curves of Fig. 2 represent R_i-values of 300 Ohm.m or 60 Ohm.m respectively, which were found to be the best average values for sands of different periods of sedimentation.

Based on these considerations we use the formula of Fig. 3 for calculating the water resistivity R_w.

The electrical conductivity of the formation is expressed as the sum of the conductivity, which is proportional to the conductivity of the water, plus the constant conductivity related to the internal surface. The latter conductivity is divided into two terms, since R_i-values of sand and clay are different, and the clay content may be derived from the Gamma Ray Log. The first of the two terms contains the internal-surface resistivity of clay and is assumed to be proportional to the clay content V_{cl}. The second term contains the internal surface resistivity of sand of the respective formation and is assumed to be proportional to $1\text{-}V_{cl}$.

R_o is evaluated from an Induction Electric Log or Focussed Electric Log, the porosity ϕ from the Density Log, and the clay content from the Gamma Ray Log.

This is, of course, an approximate formula, which tries to make use of the measured parameters as well as possible. If conductivity profiles are calculated, the results have to be observed critically and to be rechecked at any point, where a water sample is available.

We applied the formula mainly in the case of brackish and salt water. In this case the first term of the sum is dominant, the estimation of R_i is not critical and errors are mainly due to the application of the Archie formula.

In the case of fresh water in silty sands the application of the formula is problematic, because R_i depends on the grain size and silt content.

A computer program was used to calculate conductivity profiles from the well log data, which were recorded on digital tape.

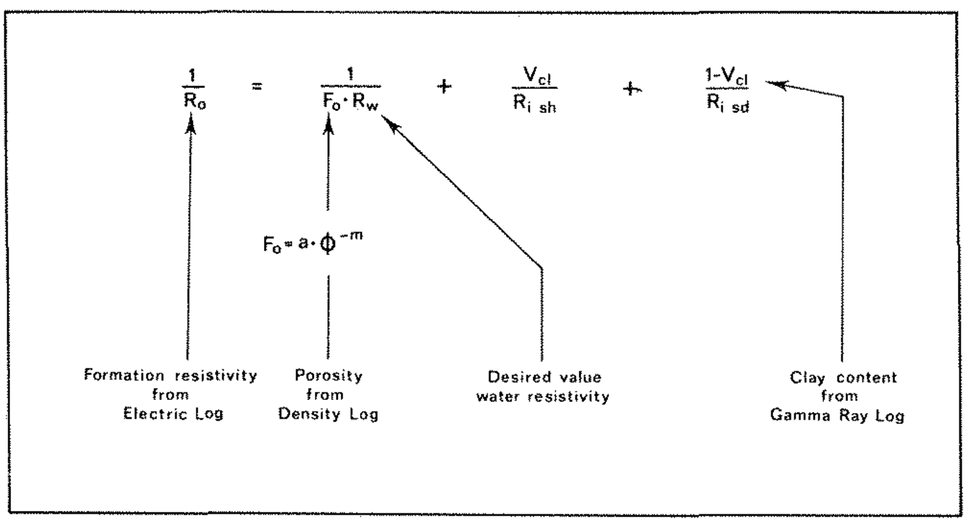


Fig. 3 – Formula for calculation of groundwater resistivity from well log data (model of parallel conductances).

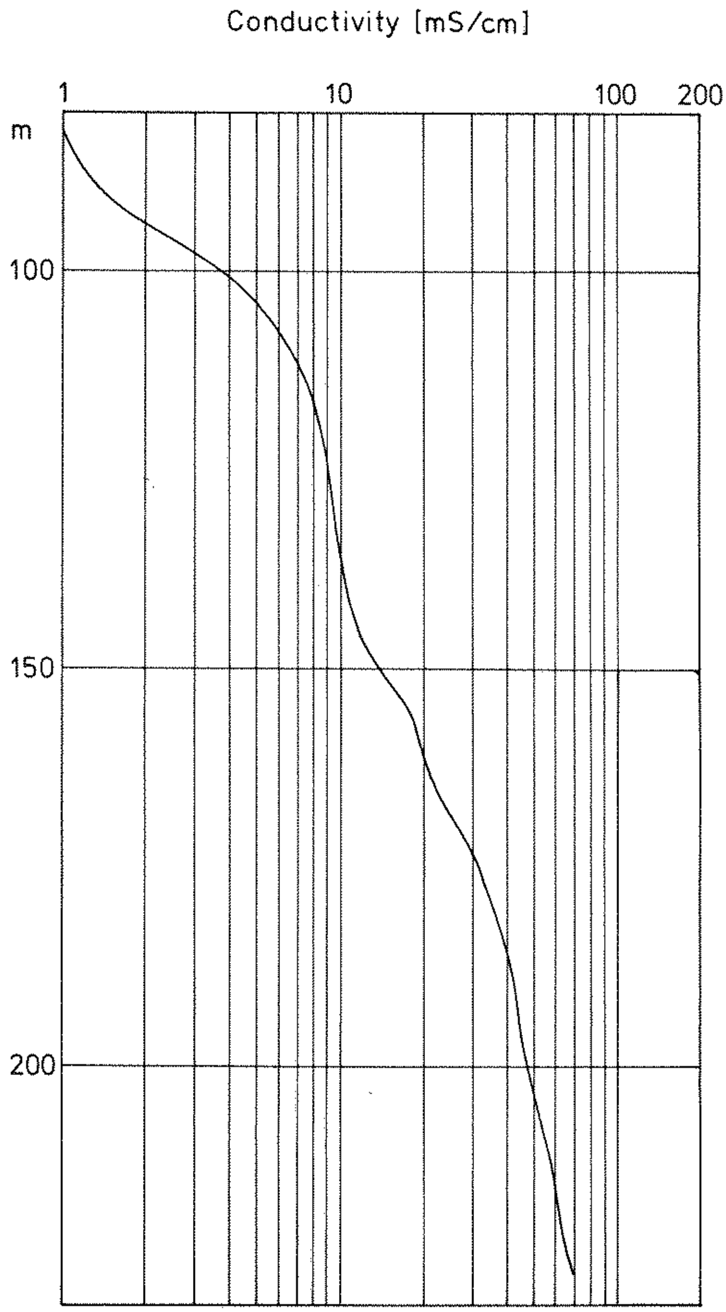


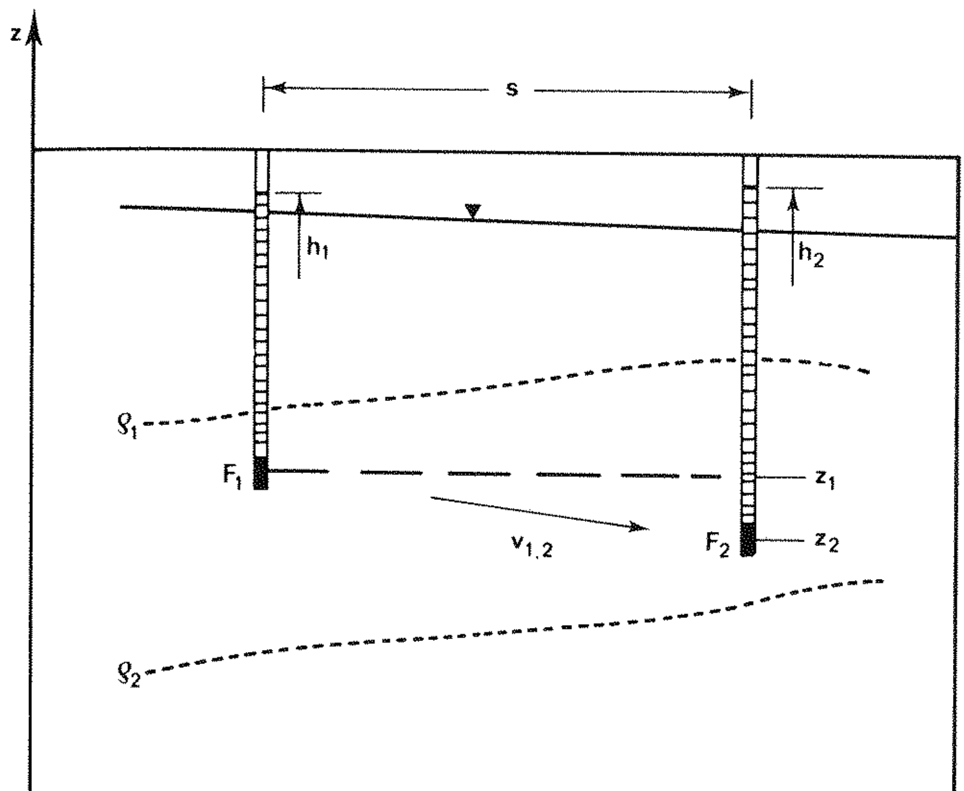
Fig. 4 – Computed log of groundwater conductivity.

Fig. 4 shows an example of a plot of groundwater conductivity. The conductivity is plotted in a logarithmic scale as mS/cm.

It increases from 1 mS/cm at 80 m depth to 70 mS/cm at the bottom of the borehole. The water-bearing formations are medium sand to coarse sand and silty sand.

Now for the study of saline water flow, the density is needed. Its calculation from conductivity data is possible if the ion content is roughly known. In our case we simply could use the conductivity/density relation of sodium chloride, because this was the dominating salt in solution.

The calculated density profiles were used for two different purposes. The first is illustrated in Fig. 5. Two piezometer wells of different depth in an aquifer with water of varying density are shown. The formula gives the average Darcy-velocity $v_{1,2}$ between filters, F_1 and F_2. K_f is the permeability, h_1 and h_2 the piezometric levels (assuming fresh water of density ρ_0 in the piezometer pipes), and $\rho(z)$ the density of the groundwater.



$$v_{1,2} = \frac{k_f}{s}\left(h_1 - h_2 + \int_{z_2}^{z_1} \frac{\varrho(z) - \varrho_0}{\varrho_0}\, dz\right)$$

Fig. 5 - Piezometers in groundwater of varying density ρ. Fresh water with density ρ_0 assumed in the piezometers, $v_{1,2}$ = Darcy-velocity.

The integral term is a correction taking account of the excess hydrostatic pressure caused by the increased density of the salt water.

The equation ho1ds only if both wells are so close together that the density may be regarded as a function of z only.

Fig. 6 shows a computed density profile at the left, and the corresponding excess hydrostatic pressure at the right. The pressure unit is meters fresh water column. The filiter positions of two wells are marked by points F_1 and F_2.

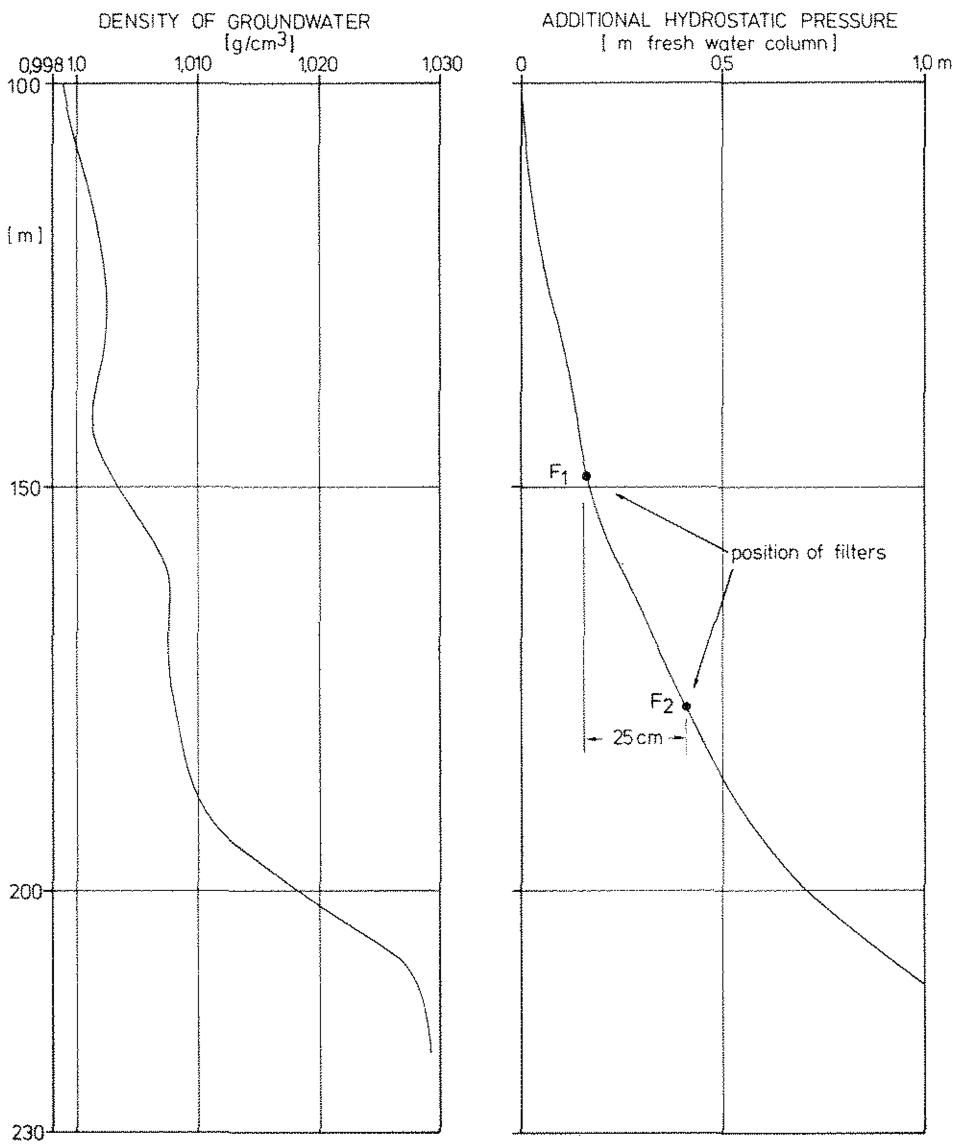


Fig. 6 - Computed logs of water density and excess hydrostatic pressure. F_1 and F_2 are filter positions of two boreholes.

The result is that 25 cm of fresh water column have to be subtracted from the piezometric level of well No. 2 (with filter F_2) before calculating the hydraulic potential difference between the two wells. From the potential difference the local flow velocities may be determined.

The procedure works sufficiently as long as the water is not very salty and the vertical distance of the piezometer filters is not too big. In that case the correction term may be much bigger than the resulting potential difference and the accuracy of the calculation is no longer sufficient.

If enough boreholes with borehole measurements and water samples are available, information of saline water flow may be got by analysing the distribution of water density in vertical sections.

Fig. 7 shows a section through a mainly sandy aquifer in about 120 to 250 m depth and on top of a salt dome.

The aquifer is separated from another one above it by silt and clay layers.

The inclined lines are lines of equal density. They mark water densities of 1050, 1100, and 1150 kg/m^3 respectively. The plotted density data were evaluated from measurements of 16 water samples and borehole measurements of 11 wells.

A transition zone about 30 m thickness is observed, where the density increases from below 1050 kg/m^3 to the density of a saturated solution.

The fresh water above the drawn section flows from the left to the right. So the inclination of the transition zone is reasonable and resembles the appearance of a salt –, fresh water boundary at the coast.

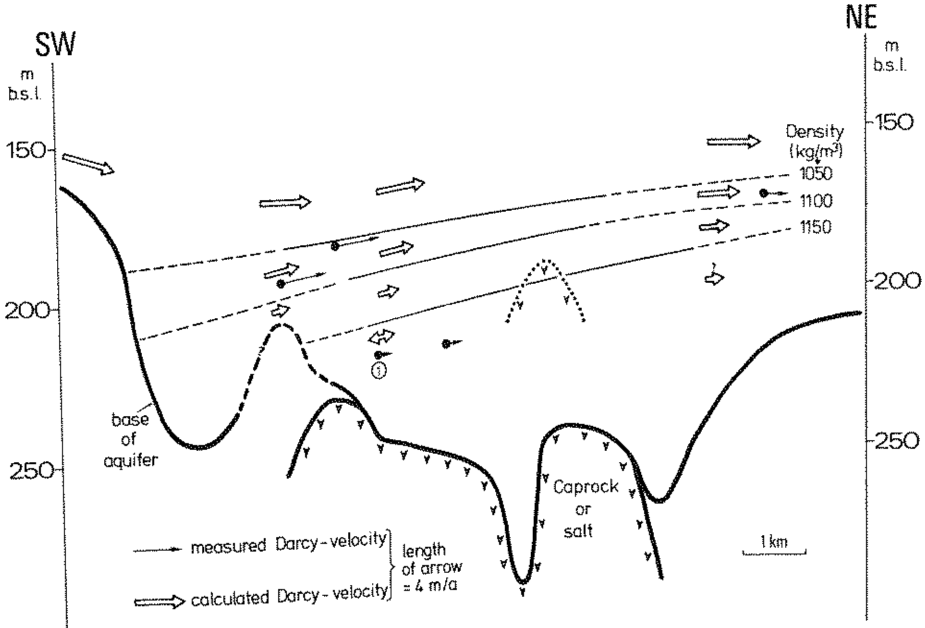


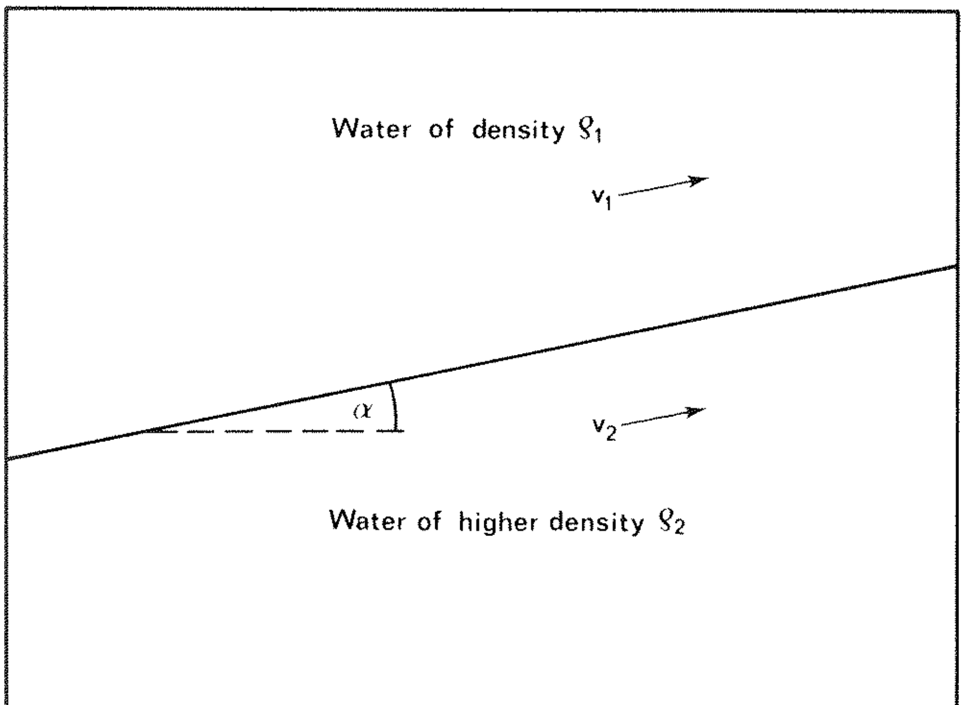
Fig. 7 – Section through aquifer on top of a salt dome, density and velocity of saline grounwater.

In this study it was an essential question to find out the flow velocities in and around the transition zone.

We used the equation shown in Fig. 8 [4]. It defines the difference of velocities above and below a density discontinuity in relation to the density contrast and the inclination of the interface. ρ_0 is the fresh-water density, and k_f the permeability coefficient at $\rho = \rho_0$. This is a general equation, which includes the Ghyben-Herzberg relation as a special case.

Regarding the density lines of Fig. 7 as discontinuities, the differences of velocities above and below each discontinuity may be calculated, if a permeability value is assumed.

The velocities will decrease from top to bottom in the shown example, and it is obvious that the flow velocity of the nearly saturated water at the left of the section will be close to zero, since no salt-saturated water can enter from the left.



$$v_1 - v_2 = \frac{k_f}{\rho_0} \cdot (\rho_2 - \rho_1) \cdot \sin \alpha$$

Fig. 8 – Velocity discontinuity at an interface between waters of different density.

Starting from here (point ①) the velocities above this point may be calculated step by step. The resulting velocities are shown in Fig. 7. The length of the arrows is proportional to the Darcy-velocity. The velocities above the transition zone are 4 to 5 m/a.

Assuming the simplified case of a constant potential gradient above the transition zone and a constant permeability, velocities may be estimated also at other points.

These velocity data are verified by velocities measured by a tracer technique.

The velocity data, particularly those at the right end of the section enabled us to estimate the amount of salt per year, which is transported away from the salt dome.

The method of determining flow velocities discussed here may seem to be quite indirect. But in this case of high salinity groundwater the direct determination of potential gradients is difficult, beacause the evaluation of piezometric levels leads to quite serious errors.

On the other hand the analysis of the density distribution derived from many sample - and well logging data has the advantage to give an overall picture of the existing flow pattern.

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