ESTIMATION OF HORIZONTAL AND VERTICAL GROUNDWATER FLOW FROM WELL-LOGGING AND PRESSURE DATA IN GROUNDWATER OF VARIABLE DENSITY ABOVE A SALT DOME

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SUMMARY

The Gorleben Salt Dome is under investigation as a candidate site for permanent disposal of radioactive waste. Hydrogeological investigations have been conducted in the area to study the aquifer system in the sediments above the dome. Well-logging provided data on the groundwater density distribution. Above the salt dome, fresh water in the upper part of the aquifer system is underlain by saline groundwater. The vertical density stratification affects the groundwater flow. Hydrostatic pressures can be calculated at any depth if the groundwater density is known. Conclusions can be drawn about vertical flow from a comparison of in situ pressure data with calculated hydrostatic pressures. Areas of overall downward or upward flow can be identified regionally in the study area.

Horizontal pressure gradients can be derived at selected depths from the in situ pressure data and groundwater densities calculated from the well-logging data. Differences in the pressure gradients at different depths can be interpreted as a change in the direction of the predominant groundwater flow in the deepest aquifer. Local deviations from the general trend of the pressure gradients at the different depths exist and indicate local effects of salt migration processes.

1. INTRODUCTION

The Gorleben Salt Dome, located in the northeastern part of Lower Saxony in Germany, is being studied as a candidate site for the permanent disposal of radioactive wastes. This salt dome is approximately 14 km long, up to 4 km wide, and its base is at a depth of about 3000 m. Hydrogeological studies have been carried out in an area of about 300 km² around the salt dome to study the aquifer system in the sediments above the dome [1]. A subglacial erosion channel, the "Gorleben Channel", more than 10 km long and 1 - 2 km wide, crosses the salt dome from south to north (Fig. 1). Erosion along the channel extends down to the cap rock and in some places down to the salt. Fresh water in the upper part of the aquifer system is underlain by saline groundwater. Groundwater movement in such an aquifer system depends to a large degree on the salinity, which influences the density of the groundwater. The vertical density stratification of the groundwater and the groundwater movement in the erosion channel is the topic of this paper.

About 160 boreholes have been drilled in the sedimentary cover above the salt dome and an extensive logging program has been carried out. In general, the following types of logs have been made in all of the boreholes: gamma ray, caliper, gamma/gamma, neutron, self-potential, temperature, and focused electric Log. When the Gorleben Hydrogeology Project was started, it was not realized how high the groundwater conductivity at depth is. The groundwater above the Gorleben salt dome has conductivities of about 0.1 mS/cm at shallow depth to about 220 mS/cm (i.e. that
Fig. 1 Location Map

Scale 1:50000

+ Borehole with Induction Log
of saturated NaCl solution) in deep sediments. It was found that the high electrical conductivity of the groundwater could not be determined from the focused electric logs with an acceptable degree of accuracy. Groundwater resistivities determined on the basis of a focused electric log are very uncertain for $R_t/R_m < 1$ (i.e. when the resistivity of rock $R_t$ is lower than that of the mud $R_m$) [2].

A large number of observation wells were drilled nearly to the depth of the cap rock. The wells were cased with PVC pipe and equipped with screens about 3 m long at the bottom. An induction log was run in 49 of the deeper observation wells. This data was used to calculate groundwater conductivity employing the formation factor concept [3]. These groundwater conductivity logs can be used to determine the groundwater density at borehole temperature. A detailed description of the method and the results are given by Ochmann [4]. Uncertainties and errors are discussed there.

2. GROUNDWATER DENSITY IN THE GORLEBEN CHANNEL

Two groundwater density logs are shown as an example in Figure 2. They show the general density distribution with depth. Groundwater mineralization increases slowly from the groundwater table down to a depth of 160 – 170 m below sea level. Below that, the groundwater density increases rapidly in a gradient layer about 30 m thick, below which highly saline water, in some places saturated brine, is found. This is due to the fact that the bottom aquifer is in some areas in contact with the caprock or the salt itself. The density of a saturated NaCl solution is about 1200 kg/m$^3$.

The groundwater densities calculated from the well logs can be verified by laboratory measurements on water samples taken at the screen depths of observation wells a few meters from the logged wells. The density values determined in the laboratory are indicated by the points in the example shown in Figure 2. It can be seen that the laboratory values are very close to the calculated curves. Nevertheless, when the deviations of all the density logs are compared with the laboratory measurements, errors of nearly 10% are found at several sites [4]. But the groundwater density profiles are generally reliable.

The density logs for the wells on a profile along the Gorleben Channel are plotted in Figure 3. The corresponding geological section is shown in the lower half of the figure. A cross section plot of the groundwater density distribution calculated from the log data along this profile is given in Figure 4. The already mentioned general distribution of groundwater density can be seen in Figures 3 and 4. The gradient of the groundwater table along this profile and other hydrogeological data show that the fresh water at the top of the aquifer system flows northeast towards the River Elbe. Thus, the lines of equal densities (Fig. 4) are not horizontal, but rise in the direction of surface water flow. This tilted transition zone between fresh water and saline water is similar to that found below islands (e.g. in the North Sea).

Assuming that steady-state flow conditions exist in the erosion channel, then the flow of the fresh water produces a hydraulic gradient in the salt water [5]. When salt migration processes are not present, the planes of equal density are parallel to the hydraulic gradient and the salt water is immobile. Because it is safe to say that salt migration processes (e.g. dissolving of rock salt, diffusion, convection currents) are present in groundwater with a salinity gradient, the salt
Fig. 2: Two examples of groundwater density distribution; the point represent laboratory measurements on water samples taken at the depth of the screens.

water cannot be regarded as immobile. Thus, water with a lower salt content must flow into the bottom aquifer to replace outflowing salt water. In the steady-state case, not only groundwater flow and the density distribution have to be taken into consideration, but also the change in density resulting from concentration gradients and the dissolving of rock salt. Thus, convection currents are produced in the groundwater above the salt dome.

A deviation from the general trend of the data can be observed in the density logs for three wells (nos. 193, 1024, & 563) (Figs. 3 & 4). An increase in groundwater density is observed at moderate depth, about 90 m below sea level. But before the depth of the high gradient is reached, the groundwater salinity decreases again. Such a salt water lens can exist only in sediments with a lower permeability than the surrounding sediments. If this is not the case, the salt water lens would have been transported away with the flow of the fresh water. We are now investigating how this salt water lens could have formed at that depth. A plausible explanation can be found in connection with glacial periods: Permafrost forms during glacial periods, stopping the flow of fresh water. Because there is no hydraulic gradient, the water below the
permafrost should be immobile. Nevertheless, the processes involved in salt migration still occur during such periods, producing a gradual increase in salt concentration. When the climate changes again, fresh water gradually replaces the mineralized water at depth.

3. VERTICAL AND HORIZONTAL COMPONENTS OF GROUNDWATER FLOW: EVALUATION OF IN SITU PRESSURE MEASUREMENTS

3.1 The Vertical Pressure Gradient

Vertical groundwater flow can be determined from the groundwater density profile in an observation well and the pore-water pressure measured at the depth of the screen of this well. Two techniques are available to determine pore-water pressure. It can be calculated from the level of the potentiometric surface in the observation wells and the groundwater density at this level or by making in situ pressure measurements at the depth of the screens. The latter method has been shown to be more reliable [6]. In our case, in situ pore-water pressure was measured at the screens of the observation wells. The precision of the measurements was about 5 mbar for a 300-m water column (corresponding to a difference of 5 cm in the height of a fresh water column).

The vertical pressure gradient $\Delta P_v$ can be calculated from the pressure $P$ measured in situ at depth $z_1$ and the calculated hydrostatic pressure as follows:

$$\Delta P_v = P - \rho(z) g dz, \quad [1]$$

where $z_0$ = depth to the groundwater table,

$\rho(z)$ = groundwater density as a function of depth $z$, and

$g$ = gravitational constant.

If the in situ measured pressure is greater than the hydrostatic pressure (i.e. $\Delta P_v$ is positive), flow is upward; a negative value of $\Delta P_v$ indicates downward flow. The value of $\Delta P_v$, however, is only an overall value for the gradient between the groundwater table and the depth at which the pressure was measured in situ; $\Delta P_v$ is not necessarily linear.

One of the aims of the investigation program was to identify areas of overall downflow or upflow above the salt dome. Since the screens of the observation wells are at different depths, the in situ pressure values are not directly comparable. Therefore, normalized pressure gradient values were used in Figure 5 rather than the in situ values. The values were normalized by dividing by the height of the water column above the depth of the measurement. This is the mean effective pressure gradient per meter water column (unit = mbar/m).

Although the distribution of wells is relatively unfavorable for constructing a contour map of $\Delta P_v$, areas of downflow and upflow can be easily identified. Areas of downward groundwater flow occur in the recharge area, which is in the southern part of the map, while in the northeastern part of the Gorleben Channel, close to the River Elbe, areas of upflow are identified. A gradual transition from downflow in
Fig. 4 Contour map of the ground-water density. Note that the scale is not equidistant.
the south to upward flow in the northeast can be observed along the Gorleben Channel. These results are in good agreement with vertical groundwater flow derived from temperature measurements [7].

![Normalized vertical pressure gradients along the Gorleben Channel indicate downward groundwater flow in the southern part of the map and upward flow in the northern part.](image)

**Fig. 5**: Normalized vertical pressure gradients along the Gorleben Channel indicate downward groundwater flow in the southern part of the map and upward flow in the northern part.

### 3.2 Conclusions on Horizontal Groundwater Movement at Different Depths

Conclusions about horizontal groundwater flow may be drawn from pressure measurements in deeper groundwater storeys in two ways:

a) Pore-water pressure can be compared at different depths in two or more observation wells, and the pressure gradient is estimated along tilted connecting lines, or

b) horizontal pressure gradients between screens at the same depths are calculated and vertical components are neglected.

Generally, groundwater movement is more easily described by separating the pressure into horizontal and vertical components than by the method of the first alternative. Calculation of horizontal hydraulic gradients has been presented in many papers. Van Dam [8] states that in aquifers of large areal extent, flow is almost horizontal. In this case it may be assumed that the vertical pressure distribution is hydrostatic. If the
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vertical density profile is known in such a case, it is possible to calculate the pressure at any point above and below the screen at which the in situ pressure was measured. It is assumed for simplification that vertical pressure gradients are negligible. If vertical flow exists, then only the hydraulic gradient in a small depth range around the screen can be obtained from pressures measured in neighboring observation wells. This will be discussed below.

So that in situ pressure measurements in neighboring wells can be compared, they have to be converted to a common depth $z_0$ using the groundwater density logs. If the depths of screens $F_1$ and $F_2$ in different wells are not too different, then the pore-water pressures $P_1'$ and $P_2'$ may be calculated approximately at a common depth:

$$
P_1' = P_1 + \int_{z_1}^{z_0} \rho_1(z) g \, dz$$

$$
P_2' = P_2 - \int_{z_0}^{z_2} \rho_2(z) g \, dz,$$

where $P_1'$, $P_2'$ = pore-water pressure at screens $F_1$ and $F_2$, respectively,

$\rho_1(z)$, $\rho_2(z)$ = groundwater densities from $z_1$ to $z_0$ in wells 1 and 2, respectively,

$z_1$, $z_2$ = depths of pressure measurement in wells 1 and 2, respectively, and

$z_2 > z_0 > z_1$.

Before we take a look at the result for the profile along the Gorleben Channel, the possible uncertainties should be mentioned. There are three sources of error:

1) Uncertainties in the values for groundwater density can be estimated only for specific points but not for an entire depth range. The density logs are believed to be quite exact, however [4].

2) Some uncertainties arise when pore-water pressures are calculated for deeper depths. Not all of the wells are the same depth and thus densities sometimes must be obtained by extrapolation from neighboring wells. Thus, the deeper the depth, the greater the uncertainty in the values for that depth.

3) As will be shown later, vertical flow exists in the Gorleben Channel. The problem is that although $\delta P$ is known between the groundwater table and depth $z$ at which the pore-water pressure was measured, it is not known between $z$ and $z_0'$, the common depth. It can be shown that $\delta P$ is not a linear function of depth [4]. Thus, a simple correction for this depth range is not possible. It is only possible to make assumptions about how large the difference between $z$ and $z_0'$ may be without causing the error resulting from neglecting $\delta P$ to become too large. The vertical pressure differences are very small in the highly saline water above the salt dome owing to gravitational effects. In the gradient layer in which the salinity rapidly increases, larger changes in $\delta P$ are possible. Nevertheless, $\delta P$ is always much smaller than the hydrostatic pressure. There is always an uncertainty resulting from the fact that the value of $\delta P$ is unknown, but the smaller the distance between $z$ and $z_0'$, the less influence this parameter has on the results.
Fig. 6 Horizontal pressure gradients in the Gorleben Channel. For explanation see text.
The horizontal pressure gradient along the Gorleben Channel profile (Fig. 6) was calculated for different depths using Equation 2. A mean hydraulic gradient along the profile at a specific depth was determined by fitting a straight-line through these pressure values (using the algorithm of Press et al. [9]). When the above-mentioned uncertainties are taken into consideration, it is more convenient to look at the general trend along the profile than at each of the individual pressure values.

The horizontal pressure gradient was calculated for depths of 160 – 220 m below m.s.l. (Fig. 6). The mean depth of the screens along this profile is 201.5 m below m.s.l. Note that the slope of the straight-lines for the general trend changes with depth. In horizontal planes groundwater flow will always occur in the direction of the lowest pressure. It is seen that at depths below 200 m the groundwater flows north-east in a gradient layer 30 m thick, i.e. the same direction as the fresh water at the surface. At a depth of 190 – 200 m, the slope of the straight-line is close to zero, implying that there is no horizontal pressure gradient at this depth.

At greater depth (210 – 220 m below m.s.l.) reversal of the pressure gradient can be interpreted as a general change of the predominant flow direction in the deepest aquifer.

4. DISCUSSION

The horizontal pressure gradient at different depths provides a good picture of the predominant flow direction at those depths. In principle, it is possible to calculate horizontal velocities from the pressure gradients in these planes. This has not been done owing to the uncertainties which cannot be estimated with an acceptable degree of accuracy. But the very small pressure gradients indicate very low flow rates at the selected depths.

Local deviations from the general trend of the pressure gradients can be seen in Figure 6. It cannot be assumed, however, that these deviations are due only to the above-mentioned uncertainties; they may also indicate local effects. It cannot be assumed that all points have to lie on the trend line, because in the Gorleben study area the groundwater body is very complex and inhomogeneous (Fig. 3). The salt concentration gradients vary in the sediments just above the salt dome. Convection currents and diffusion affect salt transport from the highly saline water to fresher water, lowering the brine concentration. The salt is replaced by the dissolving of rock salt at places where the groundwater is in direct contact with it. In a large salt-water body in which rock salt is dissolved locally, horizontal flow occurs from the dissolution area to areas of lower salt concentration. The freshwater flow may also "drag" brine from the top of the brine layer with it. This salt is replaced by the dissolving of rock salt at a different place. Under steady-state conditions, the density distribution is determined by the flow rate of the fresh water, the amount of loss of brine, and the convection currents.

The rock salt can be dissolved only locally; overlying clay layers prevent the brine from flowing away; convection currents and diffusion depend on the concentration gradient. Thus, a complex flow pattern in the saline groundwater results, in which local deviations from the general trend exist.
References


