A PALAEOHYDROLOGICAL APPROACH TO REGIONAL DENSITY-DEPENDENT GROUNDWATER MODELING: A CASE STUDY IN NORTHERN GERMANY

ELKE KOESTERS, PETER VOGEL, KLAUS SCHELKES
Federal Institute for Geosciences and Natural Resources (BGR)
Stilleweg 2, 30655 Hannover, Germany, e.koesters@bgr.de

ABSTRACT:

A hydrogeological section crossing the Gorleben site in northern Germany served as the basis for density-dependent groundwater simulations. The numerical model is used to determine climate-driven, long-term variations in the groundwater system. The model employs different types of permafrost distributions derived from a palaeotemperature curve. Time-dependent boundary conditions were obtained from palaeoenvironment data for the last glacial cycle. The simulation period begins at 120 000 BP and ends at the present. Whenever permafrost prevails, the spatial distribution of groundwater discharge is determined by the location of rivers and lakes, where taliks may form. The proximity of a glacier front during the peak period of the last glaciation has a profound influence on the groundwater movement. Inflow of meltwater at the base of the ice sheet may affect magnitude and direction of groundwater flow on local and regional scales.

INTRODUCTION

The Gorleben site is located on the banks of the River Elbe in central northern Germany between the terminal moraines of the Warthian stadial of the late Saalian in the southwest and the terminal moraines of the Weichselian glaciation in the northeast. In this area, Tertiary and Quaternary sediments form a multiple aquifer system, generally consisting of an upper aquifer of Saalian and Weichselian sands and a lower aquifer of mainly Elsterian and Miocene sands. The two aquifers are often separated by clay layers, e.g., the Lauenburg Clay and the Hamburg Clay.

During the last 120 000 years, since the Eemian interglacial, the local groundwater system around the Gorleben salt dome has been affected by the regional groundwater system, which is determined by changing climatic conditions. This is made apparent by the complex distributions of salinity and environmental isotopes in the groundwater (Klinge et al., 1999).

Interest is focused on the investigation of climate-driven, long-term variations in the groundwater system during the last glacial cycle.

To simulate the effects of such environmental changes the local groundwater model was embedded in a regional-scale conceptual model which includes all sources that might affect the groundwater flow and the associated salinity distribution on local and regional scales.

THE GORLEBEN AREA

The hydrogeological situation

A schematic hydrogeological section which crosses the Gorleben area from SSW to NNE is shown in Figure 1.

The most important aquifers consist of Miocene lignite sands and coarse-grained Quaternary glaciofluvial deposits. Intercalated clay layers and thick glacial tills of the Elsterian and Saalian glaciations, respectively, act as aquitards. In general, Palaeogene clays, especially the Rupelian Clay (Oligocene), form the base of the hydrogeological model. The most important hydrogeological features of the cross section are the Gorleben salt dome and the Gorleben erosion channel in the centre of the section. The top of the salt dome forms part of the lower model boundary. Salt can be dissolved in this area, resulting in an increased salinity of the groundwater and a density-dependent groundwater flow field in the aquifer system above the salt dome.

The River Elbe and the surrounding lowlands in the centre of the cross section are the main discharge area. During the Weichselian glacial stage, not only surface and near-surface flow through the ice marginal valley, but also the location of river beds, very probably depended on the amount of meltwater and runoff. During dry periods, drainage took place through the fluvial gravel and sand with surface runoff only in various small streams; but during high-water periods, many channels of a braided river throughout the ice marginal valley were filled, sometimes overflowing to cover large parts of the valley. There was probably no single river like the present River Elbe, which did not cut its bed into the Weichselian fluvial sands until the Holocene (Keller, 1998).

There are two major recharge areas in the SSW and in the NNE parts of the cross section. These are the hills formed by Saalian or Weichselian moraines. Groundwater flow is predominantly from these hills to the River Elbe.

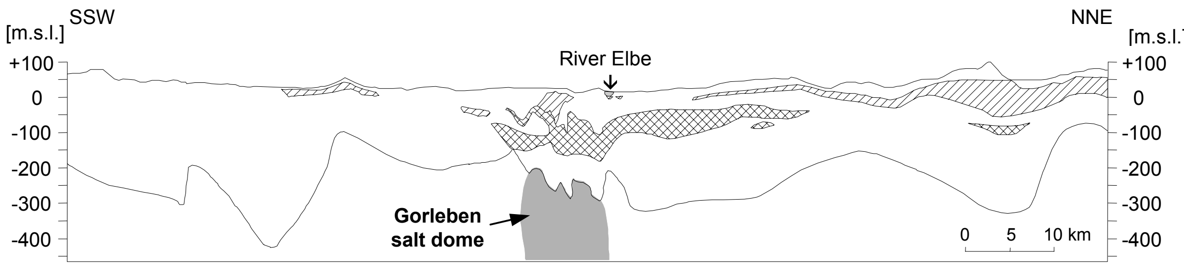

Fig. 1: Schematic hydrogeological cross section

Quaternary and Tertiary sands
Saalian clayey deposits
Quaternary and Tertiary clays

Palaeoenvironment data

Permafrost is one of the most important processes influencing the groundwater flow field and, therefore, the time-dependent development of the salinity distribution in the aquifer system. Frozen sediments were represented in the groundwater simulations by a very low-permeability layer of time-dependent shape and size.

The simulation of permafrost development was based on a palaeotemperature curve for the Gorleben region (Delisle, 1998). The

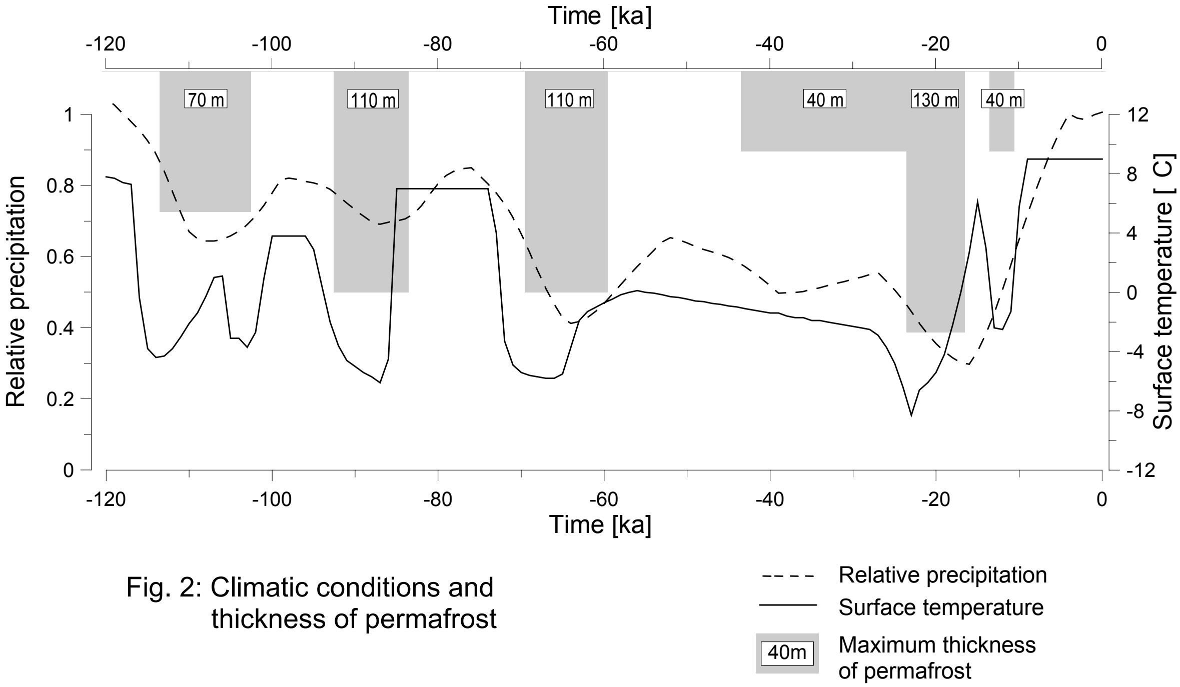

Fig. 2: Climatic conditions and thickness of permafrost

depth of permafrost is determined mainly by the mean annual surface temperature and by the locations of rivers and lakes, where taliks may form. From simulations of permafrost development four different patterns of permafrost distribution were obtained, with maximum depths of permafrost between 40 m and 130 m (see Fig. 2). These four specific patterns were then used for the groundwater flow simulations.

The simulation period of 120 000 years from the Eemian interglacial to the present was subdivided into a series of intervals. The length of each interval was selected on the basis of the prevailing permafrost distribution. Furthermore, each interval was assigned a certain precipitation, which varies between 20 % and 120 % relative to the present (see Fig. 2).

THE GROUNDWATER MODEL

Simulation set-up

The objective of the model simulations is to determine whether long-term

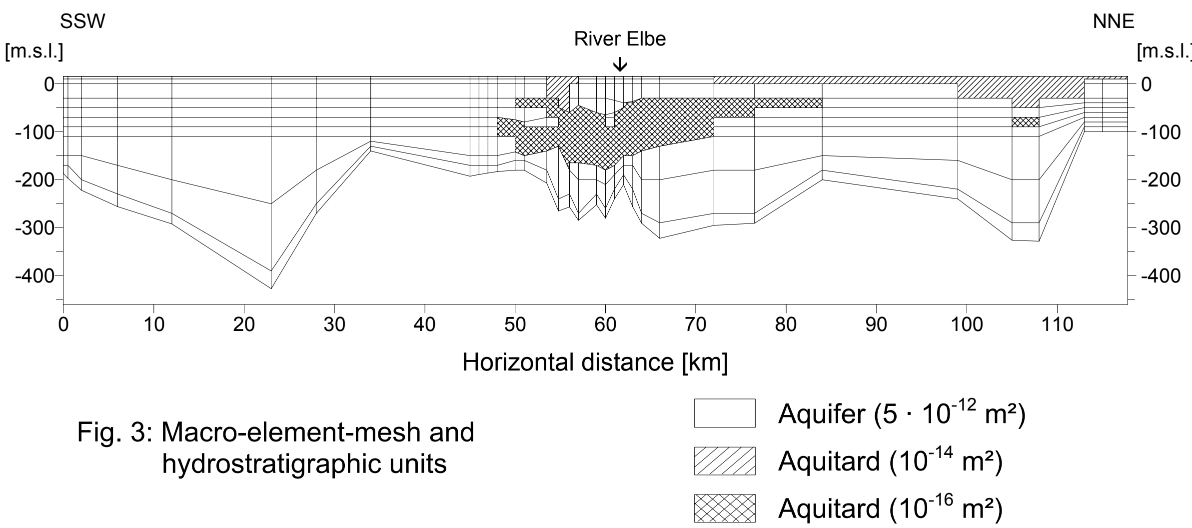

Fig. 3: Macro-element-mesh and hydrostratigraphic units

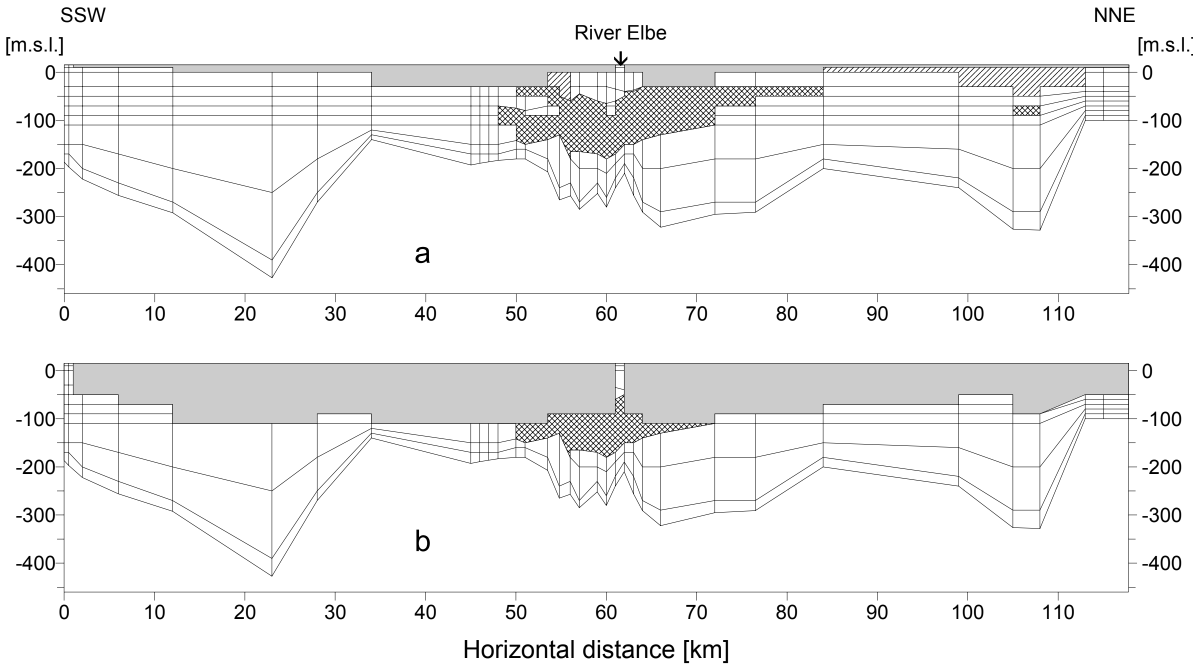

Fig. 4: Hydrostratigraphic units and permafrost distributions:
(a) maximum thickness of permafrost 40 m
(b) maximum thickness of permafrost 130 m

climate changes have a significant impact on the groundwater flow system. The schematic hydrogeological cross section depicted in Figure 1 served as a basis for the numerical model. The simulated cross section has a length of 118 km and extends from 15 m above m.s.l. down to 430 m below m.s.l. The discretization of the hydrogeological cross section and the model parameters were chosen according to the known hydrogeological and palaeoclimate conditions. The mesh consists of 4450 finite elements. Small elements were employed in areas close to taliks, e.g., near the River Elbe. Figure 3 depicts the spatial orientation of the hydrostratigraphic units. The hydrogeological model comprises three permeability classes representing aquifers and aquitards with permeabilities of $5 \cdot 10^{-12}$ m², 10^{-14} m² and 10^{-16} m². In addition, a very low permeability of 10^{-20} m² was assigned to those areas where permafrost prevails (Fig. 4).

Boundary conditions for groundwater flow and solute transport equations were chosen according to the hydrogeological situation. Time-varying pressure distributions were specified along the top of the cross section to simulate the relief of the water table. They were reconstructed from the present groundwater table and the mean precipitation history (Fig. 2)

The most important stadial was found to be the peak period of the glaciation about 20 000 years ago. Meltwater flows under high pressure at the bottom of an advancing ice sheet. The flow of meltwater into the groundwater was represented by sources at the northeast boundary of the model. The amount of recharge from meltwater was estimated using a hydraulic gradient of 0.1 (Boulton et al., 1999).

Fluid densities were allowed to vary linearly between 1000 and 1200 kg/m³ for solute mass fractions of 0.0 – 0.285. These values correspond to fresh water and saturated brine, respectively.

A solute concentration corresponding to that of saturated brine was assumed along that part of the bottom of the cross section which represents the contact with the salt dome. A solute concentration of zero, corresponding to fresh water, was specified for the water entering the system. No restriction was imposed on the solute concentration of the fluid leaving the system (i.e., free outflow). Initial solute distributions were assumed with a high salinity in the area of the Gorleben erosion channel and fresh water otherwise.

A diffusion coefficient of 10^{-9} m²/s was used. Based on experience with salt water/freshwater simulations for the Gorleben erosion channel (Vogel et al., 1993; Vogel & Schelkes, 1996), the longitudinal dispersivity for each element was set to half of the element size and a transverse dispersivity of 0 m was employed.

The SUTRA code (Voss, 1984) was used for the groundwater simulations.

Scenarios Various scenarios were analyzed to estimate the influence of the model assumptions on the groundwater flow field and the associated saltwater distribution. These scenarios included minor modifications of the model geometry or the initial solute concentration. These had only a negligible influence on the simulation results. Stronger effects on the flow field were observed by changes in the location of the River Elbe within the ice-marginal valley. However, the general trend of the salt water movement remained unchanged.

The most important influence on the groundwater flow field was recharge from the advancing glacier during the peak period of the glaciation. These scenarios demonstrate that inflow of meltwater into the aquifer at the base of the ice sheet may affect the magnitude and direction of groundwater flow on local and regional scales.

RESULTS

The simulation period begins 120 000 years ago, about the end of the Eemian interglacial, and ends at present. The various palaeo-environments are represented by the applied boundary conditions which constitute an alternating sequence of interstadials and stadials with varying thickness of permafrost.

The simulations show that the presence of permafrost appears to be of greater importance than its thickness. As a result of the imposed gradient of the groundwater table, the groundwater flow is predominantly from the recharge areas in the north and south towards the River Elbe and surrounding lowlands in the centre of the cross section. The movement of the highly saline brines at the bottom of the Gorleben erosion channel is associated with the palaeo-environmental conditions. During stadials the movement of these brines is northwards and vice-versa during interstadials.

The groundwater flow field induced by the advancing glacier during the peak period of the glaciation was investigated in more detail. Two extreme situations were simulated in which meltwater flows under high pressure at the bottom of the advancing ice sheet: (i) This meltwater flows into the aquifer underlying the permafrost (Fig. 5). (ii) The meltwater flows directly into an adjacent glacier lake (Fig. 6). The results of these simulations are presented below with main emphasis on the salinity distribution in the Gorleben erosion channel.

Scenario without a glacier lake

A series of "snapshots" is presented in Figure 5. The plots depict the evolution of the solute concentration above the Gorleben salt dome from 20 000 BP, time of maximum glaciation, to the present. At maximum glaciation, permafrost reaches its maximum depth of 130 m, a glacier advances from the north. The glacier tongue covers the permafrost and meltwater at the bottom of the advancing ice sheet is forced at high pressure into the aquifer underlying the permafrost (top of Fig. 5). Therefore, groundwater flow is to the south throughout the entire model and is strong enough to nearly completely flush the high-permeability aquifer in the erosion channel. Only small pockets of saline water remain in the northern part of the erosion channel close to the top.

The peak period of the glaciation is followed by a rather dry interstadial with only slight differences in level of the groundwater table. Hence, groundwater movement decreases, and flushing of the erosion channel stops. About 13 500 years before present, the density distribution above the Gorleben salt dome is similar to the initial conditions in which high solute concentrations are limited to areas close to the base of the channel.

The last stadial lasted about 2500 years. The simulation indicates reversal of the principal groundwater flow direction accompanied by a spreading of the brine plume above the diapir.

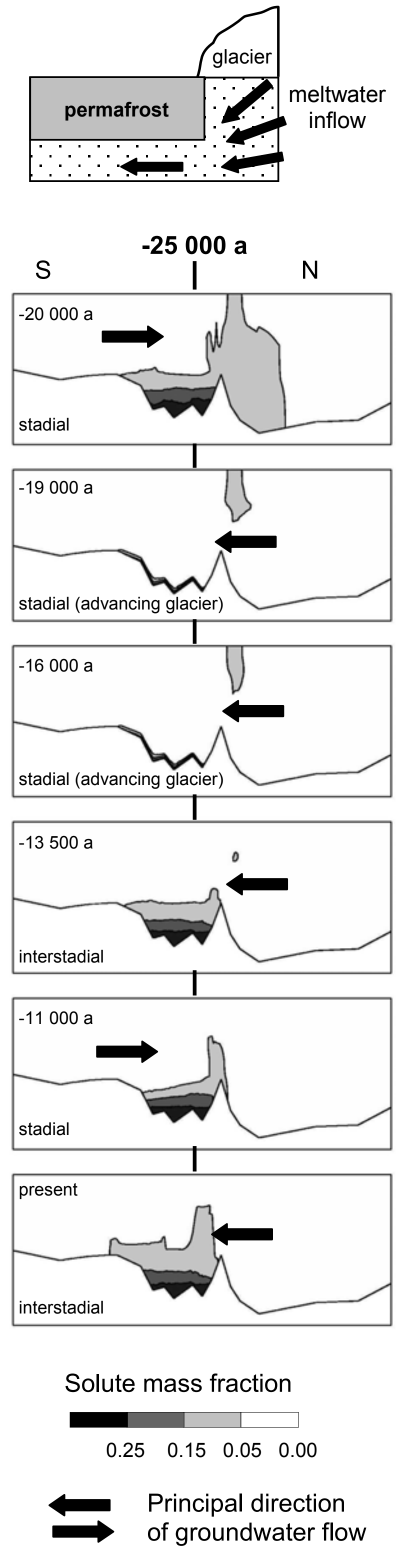

Fig. 5: Scenario without glacier lake: Temporal variation of solute distributions above the Gorleben salt dome

Scenario including an adjacent glacier lake As in the previous scenario, this one also starts at about 20 000 BP and continues the simulation of the previous period. Again, the simulated interval includes the glacial maximum and the advance of an ice sheet. However, the discharge of meltwater at the bottom of the glacier is handled in a different manner.

Due to the presence of a glacier lake in front of the ice sheet a hydraulic bypass is formed, discharging most of the pressurized meltwater directly into the adjacent lake (top of Fig. 6). Therefore, recharge from the advancing glacier has only minor effects. The regional groundwater flow is determined mainly by the imposed groundwater table.

The contour plots of Figure 6 depict the development of this scenario and the evolution of the solute concentration above the Gorleben salt dome from 20 000 BP to the present. These "snapshots" are easily compared with those of Figure 5.

The local groundwater flow within the Gorleben erosion channel is not affected by recharge from the advancing glacier. The direction of movement of the brine plume at the base of the channel changes at the transition from stadial to interstadial and vice-versa.

Comparison with the previous scenario shows significant differences during the peak period of the glaciation. However, the simulated present-day situations differ only slightly.

CONCLUSIONS

The numerical simulations show that long-term climate changes have a significant impact on groundwater flow. The results reveal some of the

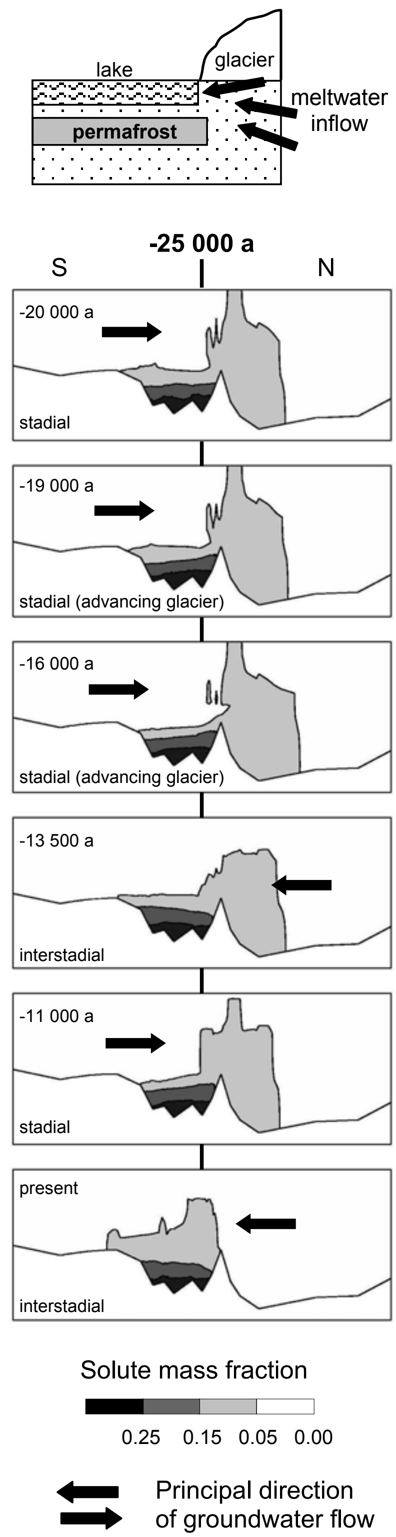

Fig. 6: Scenario including a glacier lake: Temporal variation of solute distributions above the Gorleben salt dome

hydrogeological features and parameters that have a strong effect on groundwater movement and solute transport. Whenever permafrost prevails, the spatial distribution of groundwater discharge is determined by the locations of rivers and lakes, where taliks may form. The main groundwater flow directions often change with the transition from stadial to interstadial and vice-versa.

The proximity of a glacier front during the peak period of the last glaciation has a profound influence on groundwater recharge. Recharge with meltwater at the base of the ice sheet may affect magnitude and direction of groundwater flow on a local and regional scale. Depending on the existence of a lake adjacent to the glacier, complete or partial flushing of saline water from the lower aquifer above the Gorleben salt dome may result. It follows from this study that the hydraulic conditions since that peak period about 20 000 years ago are decisive for the present-day situation in the regional groundwater system and the associated salinity distribution.

REFERENCES

BOULTON, G.S., CASANOVA, J., SCHELKES, K., GUSTAFSON, G. & MOREN L. 1999. Understanding Long-Term, Climatically-Forced Changes in Deep Groundwater Systems. In: Radioactive Waste Management Strategies and Issues, Proc. EURADWASTE '99, Luxemburg, 15-18 November 1999, p 89

DELISLE, G. (1998). Numerical Simulation of Permafrost Growth and Decay. – Journal of Quaternary Science, **13** (4), pp 325–333

KELLER, S. (1998). Permafrost in der Weichsel-Kaltzeit und Langzeit-prognose der hydrogeologischen Entwicklung in der Umgebung von Gorleben/NW-Deutschland.– Z. angew. Geol., **44** (2), pp 111–119

KLINGE, H., BOEHME, J. & LUDWIG, R. (1999). Freshwater/Saltwater Distribution in a Aquifer System above the Gorleben Salt Dome: Results of the Gorleben Site Investigation Programme.– Proc. 15th Salt Water Intrusion Meeting, Ghent, Belgium, May 25–29, 1998, Natuurwet. Tijdschr. Vol. 79 (1999), Belgium, pp 172–177

VOGEL, P., SCHELKES, K. & GIESEL, W. (1993). Modeling of variable-density flow in an aquifer crossing a salt dome – First results.- Proc. 12th Salt Water Intrusion Meeting, Barcelona, Spain, Nov. 1–6, 1992, Study and Modelling of Saltwater Intrusion into Aquifers, CIMNE, Barcelona, 1993, pp. 359–369

VOGEL, P. & SCHELKES, K. (1996). Modelling of brine transport in an aquifer crossing the Gorleben salt dome: Influences of initial conditions and hydrogeological settings.– Proc. 14th Salt Water Intrusion Meeting, Malmö, Sweden, June 16–21, 1996, Rapporter och meddelanden nr 87, Geol. Survey Sweden, Uppsala, 1996, pp 61–70.

VOSS, C.I. (1984). SUTRA: A Finite-Element Simulation Model for Saturated Unsaturated, Fluid-Density-Dependent Ground-Water Flow with Energy Transport or Chemically-Reactive Single Species Solute Transport.– USGS Water Resour. Invest. Rep. 84–4369