Long-term Saltwater Intrusion Modelling – Case Studies from North Africa, Mexico and Halle

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Introduction

Coastal saltwater intrusions threaten drinking and irrigation water resources along coastlines. On the other hand submarine groundwater discharges in nearly the same areas. The interface between saltwater and freshwater shifts over time and is mainly influenced by the seawater level and aquifer characteristics. During the last 140,000 years, seawater level fluctuation was very rapid. After a fast rising of about 120 m in the last interglacial, a slow drawdown of the same magnitude followed during the last glacial within 100,000 years. In the last 10,000 years, the water level again rose very fast and then it remained stable. Different aquifer types are influenced by these fluctuations in different ways. The two examples from North Africa and Mexico show how not only shelf platforms are flooded but also the interface in the ground water shifts over time. Both investigation areas are transboundary aquifers and the water supply of the population is affected directly by the hydrogeological development.

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Nubian Aquifer System

The interface in the Nubian Aquifer System seems to be stable nowadays but the model results show the slow dynamic effect of seawater level changes over this time frame. The amount of intrusion water is limited by the hydraulic conductivities. The flow velocities are in a range of 0.002-0.003 m/day during the times of the fastest rising seawater levels at the end of the last glacial and beginning of the holocene as shown by Gossel et al. (2010). Figure 1 shows three steps of the

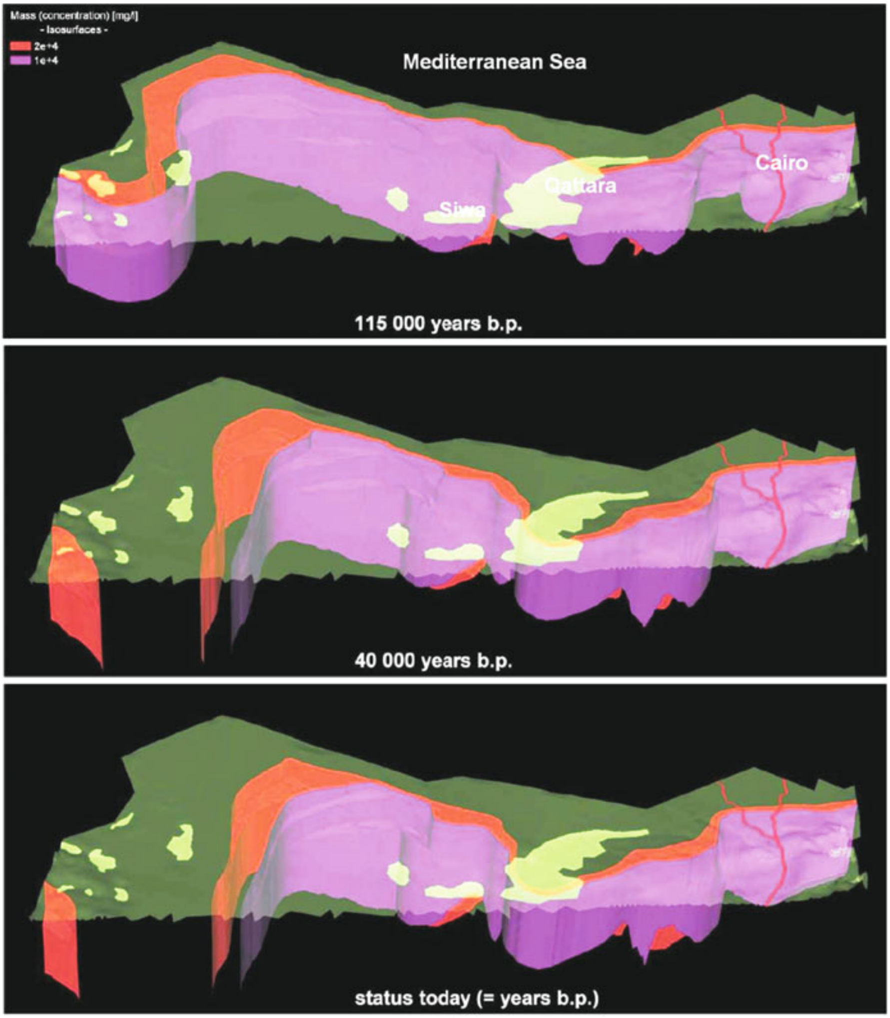

Fig. 1 Visualization of the interface at three steps during the last 140,000 years (isosurfaces of 20,000 and 30,000 mg salt/L). The first step (top) shows the situation about 120,000 years b.p. with high seawater levels at the end of the last interglacial or beginning of the last glacial. The second step shows the interface with lowest seawater levels (16,000 years b.p.) and the third outlines the interface about 10,000 years b.p. with a seawater level as today

interface movement: Infiltration of saltwater at the last interglacial about 115,000 years before present (b.p.), the deep seawater levels at about 40,000 years b.p. and after the rapid rising of the seawater levels during the last 5000 years.

Yucatan Peninsula

The karstified aquifers in Yucatan Peninsula (Mexico) react much faster on changes of climate and seawater levels. At the surface the carbonate platform of 350,000 km^2 is flooded half today so that the recent peninsula is only about 165,000 km^2 large. The rapid horizontal changes are connected to swapping of the interface in ground water, too. The fluxes of the numerical groundwater model show a high flux of fresh water out of the area (1.5-70 m/day) in times of decreasing seawater levels and in times of rising seawater levels a very high flux of saltwater into Yucatan Peninsula (1.75-75 m/day). The ingressions of several 100 km are shown in the three steps in Fig. 2.

Figure 3 shows the cross-sections of two situations: The first one during the fastest decrease of seawater level about 75,000 years b.p. and the second one about thousand years after the lowest water level (about 15,000 years b.p.). In both timesteps the depth dependent and (hydraulic) conductivity dependent distributions of saline water are clearly visible.

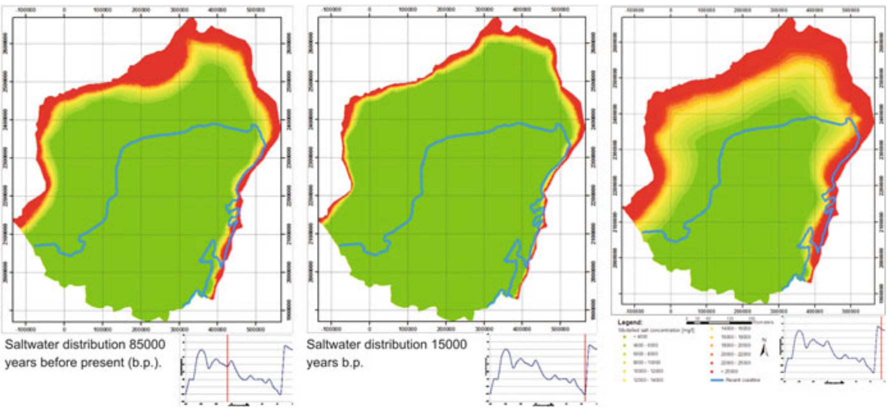

Fig. 2 Saltwater intrusion in Yucatan Peninsula over the last 140,000 years. The concentrations for the upper 100 m is responding after short times on the development at the surface

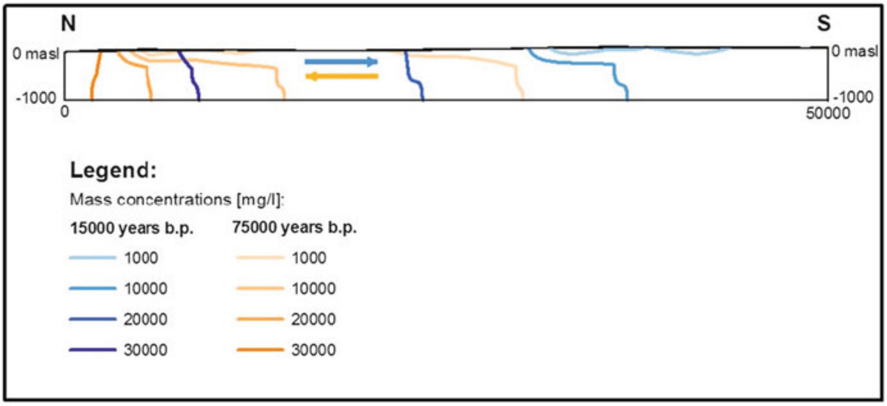

Fig. 3 Cross-section of saltwater intrusion in Northern Yucatan Peninsula. During rising seawater levels the flux into the aquifer leads to fast ingression of the saltwater with the higher density whereas the freshwater with lower density flows on top to the coast. During decreasing seawater levels the density effect is not so visible

Saltwater Upconing, Halle (Saale)

The numerical model conceptualization Halle (Saale) focuses on inland saltwater intrusion or saline deep waters along regional fault systems, respectively. This brine water uptake constitutes a danger for the shallow freshwater aquifers in terms of salinization and therefore harms potentially the local drinking water supply of the urban area. In historic ages, the occurrence of shallow accessible high saline waters has been an outstanding reason for tended population settlements and economical utilization. According to this, the major city Halle (Saale), Central Germany, owes its historical foundation on the uptake of high saline deep waters which is linked to the presence of a complex geological fault system of regional scale.

Since the early 19th century, the upcoming saline water fluxes along the fault system declined noticeably due to anthropogenic impacts, mainly mining related groundwater pumping. As the regional mining activities were given up at the end of the last century, a phase of groundwater rebound was initiated that is linked to a re-activation of the geological fault system and related saline water uptake dynamics. With respect to this, the saline water became subject of research for estimating their impact on probable near-surface salinization processes.

As the complex geological fault system defines and influences significantly the saline hydrodynamics, its spatial characterization and three-dimensional conceptualization constitutes the essential structural model input for numerical experimentations on related fault system hydrodynamics.

In recent years the geological structure of the fault system was revised multiply based on regional geophysical investigations which provided the conceptual model database of a previous 3days fault zone modelling. With respect to the three-

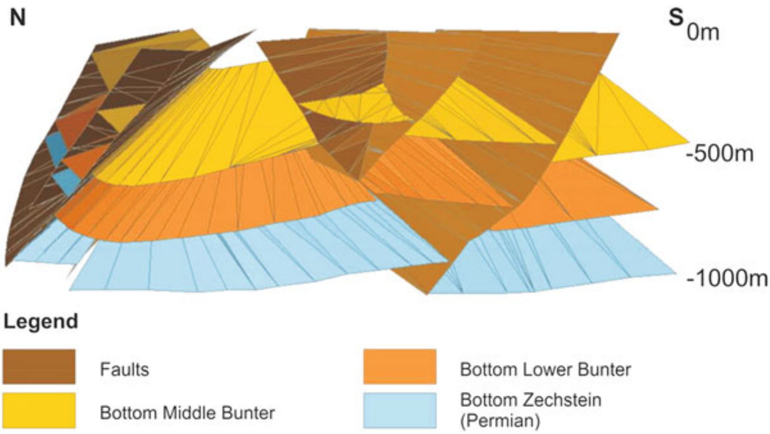

Fig. 4 View into the 3D structural model of Halle (Saale). Tectonic dislocations effect a displacement of the geological units along the steep fault planes. (Lähne et al., in prep.)

dimensional representation of the fault system (Fig. 4), information about the orientation of fault planes, structural intersections as well as volumetric and spatial information about involved geological units is available.

Based on the 3D fault model, a two-dimensional cross-section of about seven kilometres length was extracted that comprises geometries of respective geological units and regional faults. Subsequently, this section was transferred into a finite element model and was spatially discretized into 545,000 model elements.

Beside river level data and data of the regional groundwater monitoring, the numerical flow model was parameterized with characteristic hydraulic conductivity values which were derived from hydraulic laboratory tests, in-situ pumping tests and slug-and-bail tests.

The analysis of current and historical measurement data or literature indicates local highly confined aquifer conditions in the lower Zechstein formation which is interpreted simultaneously as the driving force of the regional saline water uptake.

The hydrodynamic modelling approaches under currently measured conditions (Fig. 5, Zechstein unit: +89 m NHN) shows almost no regional uptake dynamic along the fault system but confirms confined conditions ESE part of the cross-section.

The simulation results of the 2-D steady-state flow simulations were analysed and visualized regarding respective hydraulic head patterns and advective flow velocity fields. Moreover, conservative particle tracking was used to illustrate advective flow pathways of imaginary particles. Flow direction arrows describe the hydrodynamic situation along fault lines that were derived from previous simulated velocity fields.

For hydrodynamic experiments (Stollberg et al., 2012), the investigated and generic hydraulic head potentials were defined and assigned to the model, to study their hydrodynamic effects onto the groundwater flow regime. With respect to the high mineralisation of the deep waters a density dependent correction was required for the assignment of the hydraulic head scenarios.

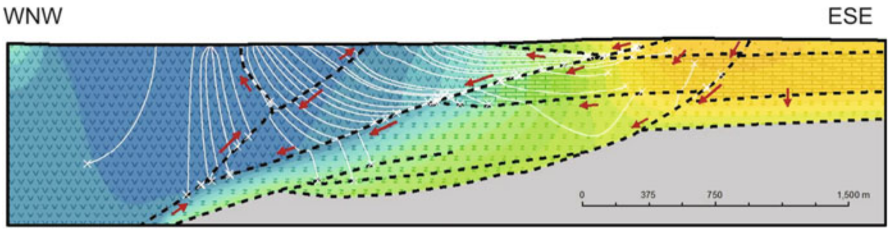

Fig. 5 Based on current hydraulic head conditions (Zechstein unit: +89 m NHN), simulation results do not indicate clear water uptake dynamics along geological unit boundaries, lineaments or tectonic fault lines. Rather, the flow velocity patterns signify a regional drainage effect of the studied fault system

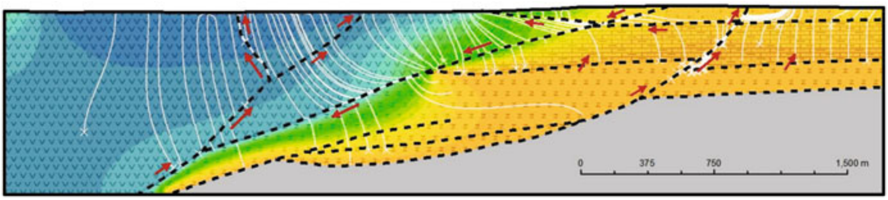

Fig. 6 A hydraulic head scenario of +101 m NHN indicates a clear water uptake along selected fault lines. Principally in the eastern part, high saline water uptake directly from the Zechstein unit is highly probable. Here, a local upward movement is additionally proven by generated pathlines

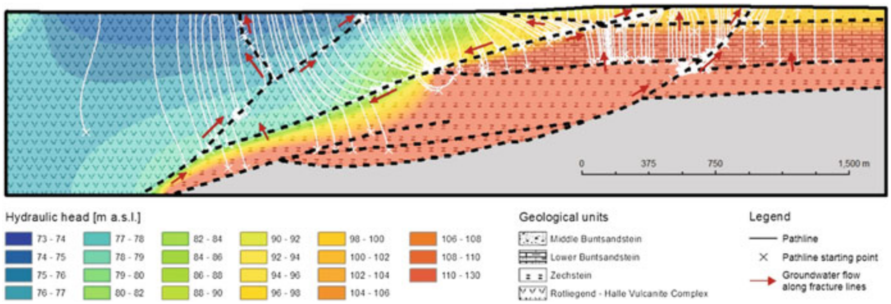

Fig. 7 Highly confined conditions of the Zechstein unit activate all fault lines for a general water uptake in the Permian and Triassic aquifers based on numerical experimentations. Here the sensitive hydraulic head range varies between +110 and +125 m NHN. In particular, the full hydraulic penetration of the dislocated Zechstein block is noticed

With respect to Fig. 6, a prescribed head of +101 m NHN was assigned to the top surface of the Zechstein unit which activates the most eastern fault line for water uptake. Moreover, fully upward oriented flow dynamics is implied by respective flow vectors and related pathlines along the western fault line.

With respect to the highly confined Zechstein scenario of Fig. 7, a general upward movement of potential deep saline waters of the Zechstein aquifer is observed. From a hydraulic point of view, all fault lines could be activated for deep water uptake, except a local fault segment which is characterised by a significant positive hydraulic conductivity contrast. This hydraulic fault line activation is observed within a hydraulic head range of the Zechstein unit from +110 to +125 m NHN.

Currently, local investigations are running to specify respective mixing effects along the deep saline water and freshwater interface based on a density coupled transport modelling. Here, the calibration of the density coupled transport model is quite difficult since available data about the mineralisation and distribution of deep waters is generally rare or challenging to estimate. The recent drawdown of uptake dynamics led to a regional freshwater intrusion which was observed over the last twenty years and could be verified by the modelling approach. Moreover, the re-activation of respective fault lines as the minor uptake pathways of saline deep waters in combination with realistic pressure conditions within the Permian and Triassic aquifers could be confirmed as well.

For giving an appropriate risk assessment concerning the salinization potential of the shallow freshwater resources, the on-going density-coupled transport study is inevitable.

References

Gossel, W., Sefelnasr, A. and Wycisk, P. (2010). Modelling of paleo-saltwater intrusion in the northern part of the Nubian Aquifer System, Northeast Africa. *Hydrogeology Journal*, **18:** 1447–1463.

Lähne, R., Stollberg, R., Gossel, W. and Wycisk, P. (in prep.). Geological fault zone modelling and its application to numerical experimentations on saline groundwater uptake – Case study, Central Germany.

Stollberg, R., Lähne, R., Rappsilber, I. and Gossel, W. (2012). Hydrogeologische Interpretationen zur Dynamik des historischen Salzwassseraufstieges der Stadt Halle (Saale). *In:* Liedl, R., Burghardt, D., Simon, E., Reimann, Th. and Kaufmann-Knoke, R. (Hrsg.): Grundwasserschutz und Grundwassernutzung – Modelle, Analysen und Anwendungen, Schriftenreihe der DGG, Heft 78, Dresden.