DENSITY DEPENDENT FLOW MODELLING: APPLICATION TO THE JORDAN VALLEY

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ABSTRACT

Problems of groundwater utilization in the Jordan Valley concern certainly the quantity of available water but also its quality: Increasing salinity is encountered in the vicinity of the Dead Sea and presents also a problem in areas further north. Part of a joint research effort involving German, Israeli, Jordanian and Palestinian partners is the numerical simulation of density dependent groundwater flow. The objective of the numerical simulations is to validate hydrogeological models especially with respect to possible sources for the salinity observed today. Along the Jordan Valley 3 typical cross sections were identified and subsequently modelled. The numerical models yield reasonable results and thus strengthen confidence in the hydrogeological models.

INTRODUCTION

The scarcity of the Middle East's water resources is well known and often discussed (e.g. Green Cross International 2000, 1999 and Brooks 1997). A growing demand for fresh water has lead to an intensive exploitation of groundwater resources and extraction rates often exceed safe yields. In addition to declining water levels groundwater utilization in the Jordan Valley and adjacent aquifers is hampered by increasing salinities: When groundwater exploration first commenced in the early 1970s, the waters in all the wells along the western border of the Jordan Valley were of a Ca-Mg-HCO_3 type. After a few years of pumping the water in some wells changed to a Na-Cl water type. (Guttman, 1998). The increase of salinity is encountered in the vicinity of the Dead Sea but also in areas further north.

A research project involving German, Israeli, Jordanian and Palestinian partners was formed to improve the understanding of the hydrogeological situation within the Jordan Valley and adjacent mountain aquifers. Part of the joint research effort is the numerical simulation of density dependent groundwater flow. The objective of the numerical simulations is to check the consistency of the hydrogeological models especially with respect to possible sources for the salinity observed today.

The general approach is to identify typical EW oriented cross sections and to examine the flow regime in those simplified 2D cases. This report deals with the development of the hydrogeological cross sections and first results of the numerical simulations are presented. Model calibration, the examination of density effects and the effects of unconfined flow will be examined at a later stage of the project

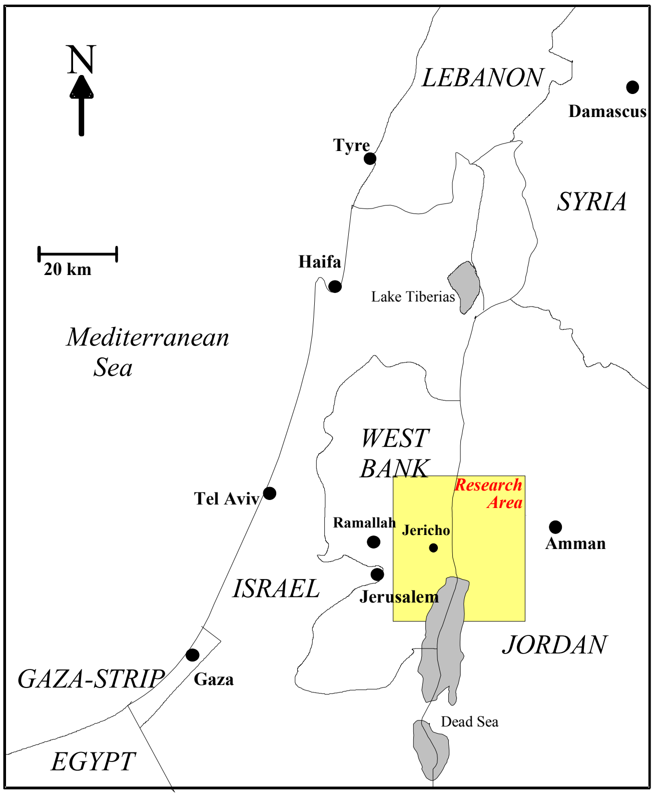

***Figure 1** Location map*

REGIONAL SETTING

The area of interest is located to the North of the Dead Sea and covers an area of about 1500 km² (Figure 1). Elevations range from more than 800 m above sea level (asl) at the flanks of the basin to 410 m below sea level (bsl) at the Dead Sea. Large elevation changes are also reflected by climatic variations: On the high mountains in the west average rainfall reaches 550 mm/a and decreases to less than 100 mm/a on the Dead Sea shores. The Jordan Valley forms a fault-bounded structure in a still active strike-slip basin. To the north of the Dead Sea subsidence reached 8 – 10 km (ten Brink et al., 1993). The valley is filled with marls, clays and partly with coarser grained alluvial deposits. The flanks of the basin consist of Cretaceous sequences of the Judea and Mount Scobus Group on the western side, and sandstones, siltstones as well as limestones and marls of Palaeozoic and Mesozoic sequences on the eastern side (Figure 2).

HYDROGEOLOGICAL MODEL

Structural Framework

The general framework of the hydrostratigraphical units is illustrated in the cross sections of Figure 2 and briefly described below. The subsurface of the West Bank can be subdivided into the following major units:

- Upper Aquifer comprising limestones and dolomites of the Bina-, Weradim-, Kefar Shaul Avnon- and Aminadav Formation (un/us/ud/uw/uav/au).
- Middle Aquiclude comprising marl and clay, sometimes limestones and dolomites of the Moza-, Bet Meir-, Kesalon- and Soreq Formation (uey/uke/us).
- Lower Aquifer comprising limestones dolomites and sometimes marl of the Givat Ye’arim- and Kefira Formation (ugy/k).

The properties of the Mount Scobus Group vary depending on which formations are present and are treated as aquiclude or aquifer. The base of the system is defined by marls of the Quatana Formation (lq). The hydrostratigraphic units of the East Bank are:

- A1/6 Aquitard comprising marl, limestone and dolomite of the Ajlun Group.
- Kurnub Aquifer comprising sandstone of the Kurnub Group.
- Zerqa Aquitard comprising mostly siltstone of the Zerqa Group.
- Ram Sandstone Aquifer.

The A7/B2 Aquifer is present only in some areas along the rift valley and of minor importance regarding groundwater flow towards the Jordan Valley Basin. It is therefore omitted from the hydrogeological model. Rocks of the Precambrian basement define the base of the system on the eastern side.

Little is known about the detailed succession of sediments within the Jordan Valley. Even though coarser grained alluvial deposits occur close to present or historical wadis may play an important role for local water supplies, the substantial part of the sediments has a generally low permeability.

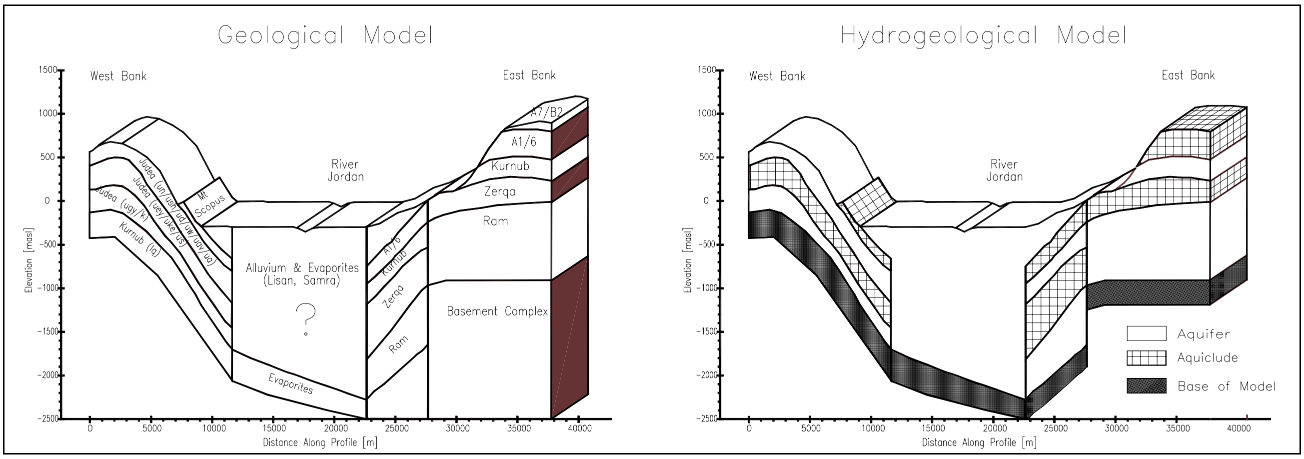

Figure 2 *Geological and hydrogeological model of cross section 1 (Modified after Klingbeil et al, 2000)*

Groundwater Flow

Due to low rainfall depths and high evaporation rates recharge to groundwater within the Jordan Valley is almost non-existent. During flooding however recharge occurs locally in alluvial fans within the valley. On the West- and East Bank however recharge rates are higher due to high precipitation in the winter months. The general flow direction is from those mountain belts towards the rift valley. Outflow occurs at springs and direct subsurface discharge into the Dead Sea as well as abstraction wells situated along the rift valley.

Faults may have an important effect on groundwater flow. Time domain electromagnetic measurements did show a steepening of the salt/fresh water interface across the fault from the Dead Sea towards the West Bank. The steepening interface could be modelled best with low horizontal- and higher vertical permeabilities within the fault zone (Yechieli et al. 2001).

Sources of Salinity

Regarding possible sources of salinity water historical Dead Seawater levels are important to consider: 15,000 years ago the water level reached with about 230 m above the present Dead Sea level its maximum. The Lisan Sea, a precursor of the present sea, covered large areas of the Jordan Valley up to an elevation of 180 m below sea level at that time (Begin et al. 1974). As a result the underlying rocks and sediments were saturated with saltwater. Assuming homogeneous conditions and a general groundwater flow from the Sea of Galilee to the Dead Sea the time required to flush the saltwater out of the Jordan Valley fill can be estimated using:

$t = V/Q = (x^2 n) / k * \Delta h$

where
- V is the volume of saltwater to be displaced
- Q is the discharge
- x is the length of the inundated Jordan Valley
- n is the porosity
- k is the hydraulic conductivity
- Δh is the head difference between h at the northern and southern end of the inundated Jordan Valley

Assuming x = 40,000 m, n = 0.1, k = 1 10^{-7} m/s and Δh = 200 m the time required to flush the system completely is more than 2 million years. Hence: Flushing could not have occurred for the whole valley fill after the last inundation 15,000 years ago. Residual brines are therefore a potential source of salinity throughout the Jordan Valley not only at large depths.
Other possible sources of salinity are buried salt bodies detected by seismic reflection (Niemi, 1997) or hot brines situated in deeper aquifers resembling the situation proposed for saline springs at the Sea of Galilee (Gvirtzman 1997).

PROCESS MODEL

Modelling Approach

Whereas the structural framework of hydrostratigraphical units present is relatively uniform along the Jordan Valley and closely resembles the geometry given in Figure 2 there are differences regarding:

- potential heads at the model boundaries as a result of different topographical elevations
- location of sinks (wells at different depth or springs)
- location of salt water body

Three typical cross sections were identified and subsequently modelled numerically. Their location is seen in Figure 3.
A note of caution is necessary at this point: The models are not designed to make absolute quantitative predictions as no model calibration has been performed at this stage of the study. The objective of the numerical simulation is to test the plausibility of the hydrogeological models and to gain insight into the system as a starting point for the development of a 3D model.

Model Set-up

An overview over the model geometry and chosen initial- and boundary conditions is given in Figure 4 and Figure 5. Recharge is not modelled in any cross section. Water enters the domain through the defined hydrostatic head distribution along the western and eastern boundaries. Residual brines as source of salinity are represented by high initial concentrations of 340 g/l. Groundwater discharge occurs from wells penetrating the lower aquifer in cross section 1. The residual brines are assumed to be situated at a depth of 1100 m bsl and have not reached the Lower Aquifer yet. For cross section 2 the salt source is assumed to be a reservoir of residual brines situated at a depth of 800 m bsl. Here the brines are present in the lower aquifer and groundwater discharge is taking place from wells in the upper aquifer. No artificial groundwater extraction is taking place in the scenario modelled in the 3rd cross section. On the western side the Fascha wells act as sinks, on the eastern side the Zerka Ma'in wells at an elevation of around 0 m asl (Salameh 1985). Also some water is lost to the Dead Sea.

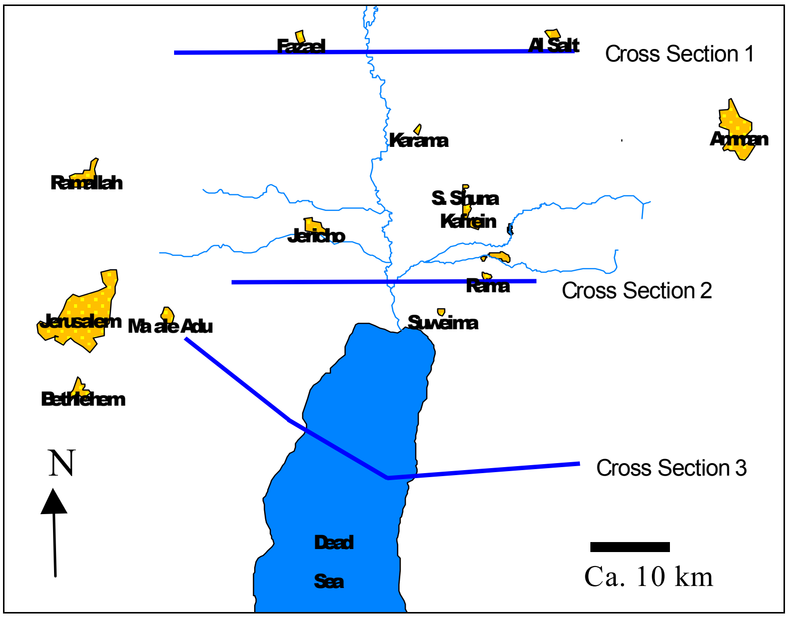

Figure 3 *Location of cross sections*

Every cross section is discretized by ca. 4000 elements. Longitudinal dispersivity is 100 m and transverse dispersivity 10 m and water density is approximated by a piece-wise linear function.

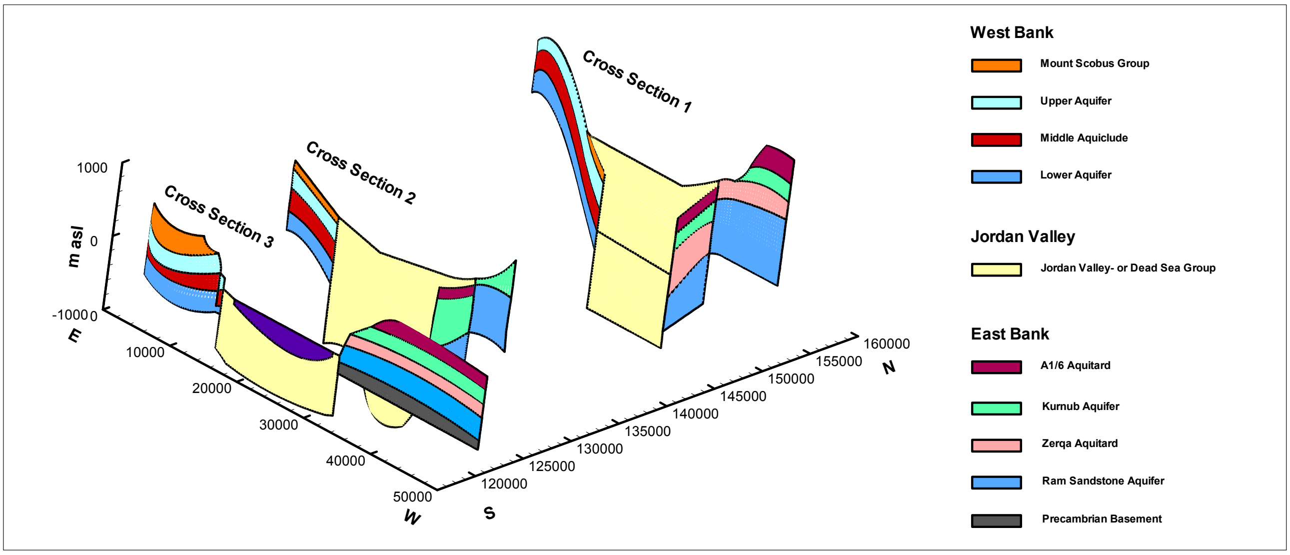

Figure 4 *Model geometry*

The Modelling Code

The numerical simulations were performed using the simulator RockFlow (Kolditz et al. 2001). RockFlow uses a finite element approximation for 2 or 3D flow problems. The program has been verified against the Henry, Elder and the salt dome problem (Kolditz et al. 1998) and can also employ an automatic grid adaptation routine to obtain stable solutions at sharp concentration fronts (Kaiser 2001 and Thorenz 2001).

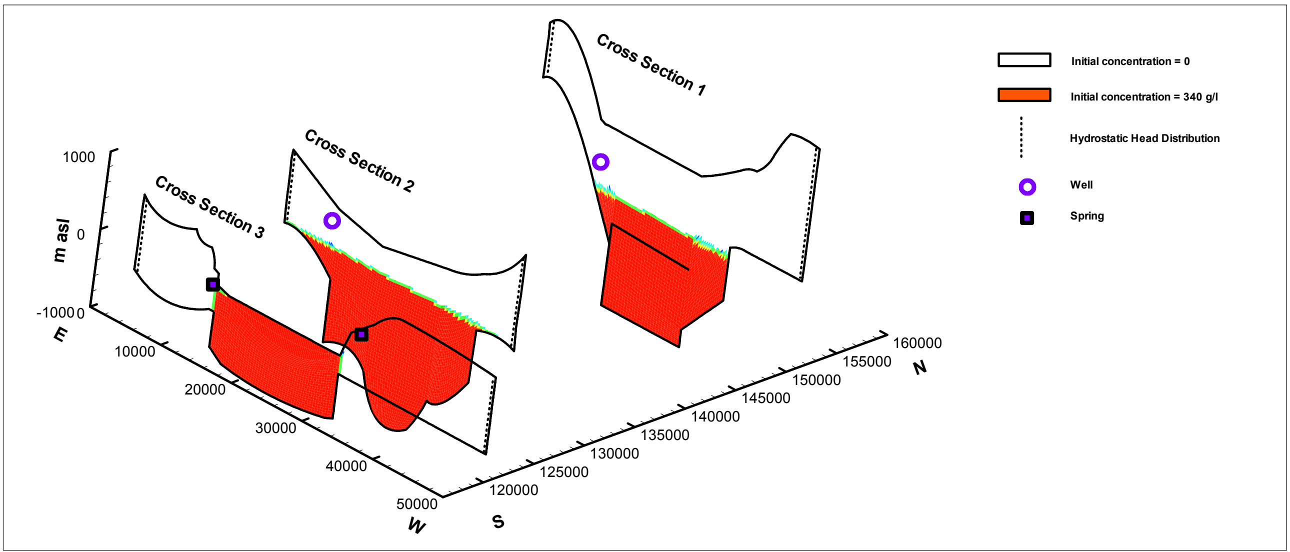

Figure 5 *Initial conditions and boundary conditions*

RESULTS AND DISCUSSION

Figure 6 shows the development of salt concentrations versus time for pumped water in the wells of cross sections 1 and 2. The modelled saltwater appearance coincides approximately with the actually observed behaviour. No calibration has been performed at this stage of the project for a number of reasons: The physical system of cross section 2 is not properly represented by the model as unconfined flow is not yet incorporated into the modelling software. Data for appropriate boundary conditions has not been made available yet and volumes extracted from a radial system are difficult to convert into volumes appropriate for 2D sections.

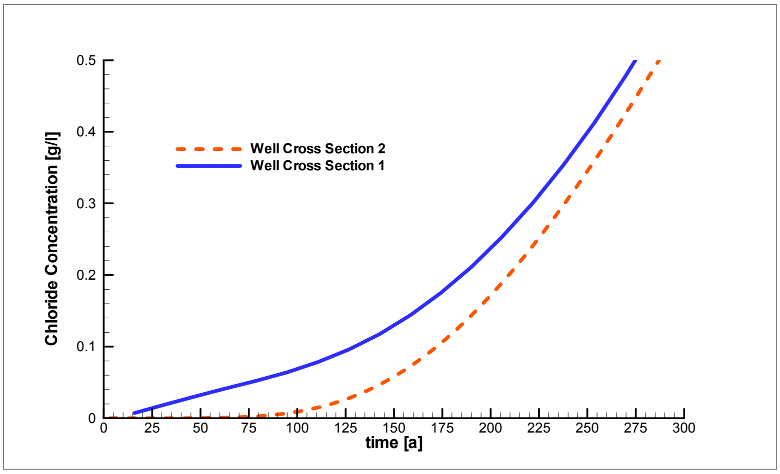

Figure 6 *Modelled concentrations in pumping wells*

CONCLUSIONS AND FUTURE WORK

The numerical model yields reasonable results and thus strengthens confidence in the hydro-geological model. As a consequence these cross sections will serve as a starting point for future modelling studies. The implementation of a free surface approach to model unconfined flow is identified as a prerequisite to properly represent the physical system, especially with respect to the hydrogeological scenario given at cross section 2. A further step will be the expansion of individual sections to quasi-3D models with subsequent stationary and transient model calibration.

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