Development of a regional groundwater flow model along the western Dead Sea escarpment

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Abstract Water is a scarce resource in the semi-arid to arid regions around the Dead Sea where the precipitation events occur mostly in winter. Average precipitation values ranges between 50 and 600 mm/year. Because of the Dead Sea Graben structure the distribution of precipitation shows a sharp drop over a short distance from the mountainous area towards the Dead Sea. But the area around the Dead Sea is also characterized by a high population density. Therefore the present study deals with the investigation of the water budget of the western Dead Sea escarpment. A main goal is to understand the subsurface water balance of the western Dead Sea escarpment and the impact of the lowering of the Dead Sea water level. The study area is limited by the subsurface watersheds and has a size of ~4000 km^2. The region is characterized by the heterogeneous aquifer system of the Judea Group. The formations of the Judea Group are separated in two sub-aquifers, the Upper Cenomanian-Turonian aquifer and the Lower Cenomanian-Albian aquifer. The objective is to quantify the surface and subsurface inflow of the western escarpment into the Dead Sea basin. This paper gives an overview of the developed regional groundwater flow model of the western Dead Sea escarpment which was achieved by the scientific software OpenGeoSys (OGS), which is specialized in coupled hydro systems processes and calculates the groundwater flow in porous and fractured media of the aquifer system (OGS 2011). The advantage of OGS is the detailed processing of the geological formations and structures (e.g. faults).

Key words numerical modelling; structural model; 3D groundwater flow model; OpenGeoSys; arid region; Israel, West Bank

INTRODUCTION

The challenge of this work was to build up a geometrically complex three-dimensional (3D) finite element model for the simulation of groundwater flow in the Turonian-Cenomanian Aquifer system (Cretaceous) of the western Dead Sea escarpment (Israel and West Bank) on the basis of scarce data. The model should help to understand the subsurface water balance of the western Dead Sea escarpment and the impact of the lowering of the Dead Sea water level. Therefore a structural model was developed by using different hydrogeological modelling techniques using software such as GMS, ArcGIS and finally OGS. The numerical modelling of the complicated hydrological processes can be described by mathematic equations and specific boundary conditions. These equations were solved by finite element method using numerical solvers included in OGS. The numerical model under steady state conditions was calibrated based on limited data of hydraulic heads of observation wells and hydraulic conductivities. The experiences of each additional model run lead to gradual refinements of the hydraulic conductivity and improve the model accuracy.

CONCEPTUAL MODEL

The study area (Fig. 1) is located in the Middle East, at the western shore of the Dead Sea. It is bounded in the north by the city of Jericho (West Bank), in the east by the shore of the Dead Sea, to the south by the desert Negev and to the west by the mountain range of the Judean Mountains (Israel / West Bank). The maximum extension of the subsurface groundwater catchment of the study area is 130 km in a north–south and 60 km in a west–east direction and extends over an area of ~3800 km^2. The stratigraphical profiles in the study area vary from Lower Cretaceous age (composed mainly of limestone layers) to young formations of Holocene age, with chalky, marly and clayey layers (Guttman, 2000). The 3D groundwater model comprises all relevant stratigraphical layers (Aquifer and Aquicludes) of the Turonian-Cenomanian Aquifer system up to the recent Quaternary sediments.

Because of the steep gradient in elevation from the highest point of the study area (Judean Mountain) to the lowest point (Dead Sea), there is a high variation in the distribution of the annual precipitation. In the Hebron area (Judean Mountain) the maximum rainfall (650 mm) has been observed by Kronfeld & Rosenthal (1987). There is a gradual decrease in the sum of precipitation towards the Negev desert to 100 mm/year with rainfall events occurring exclusively during winter. The minimum average annual rainfall of 80 mm/year occurs along a small hyper-arid longitudinal zone running along the Dead Sea coast. Temperatures vary from an annual average of 17°C in the western part of the study area to 24°C along the southern Dead Sea area (Flexer *et al*., 2009).

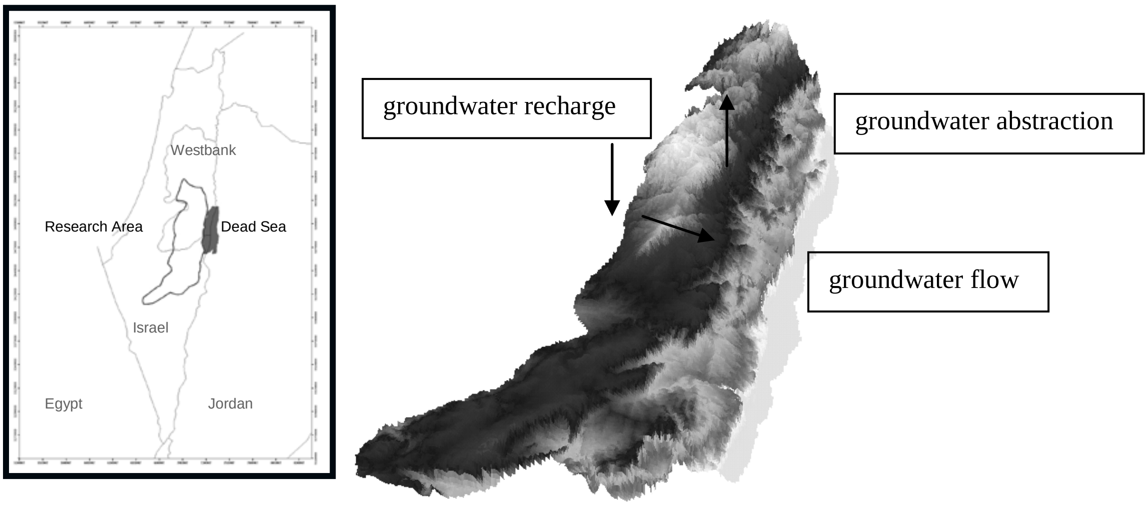


Fig. 1 Study area and conceptual model.

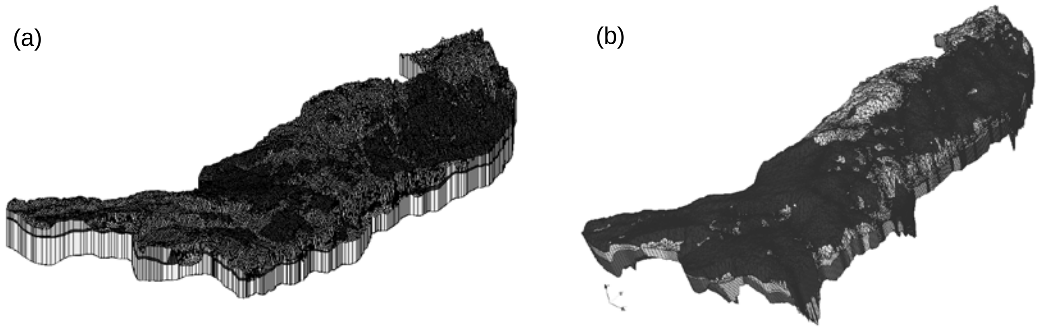
STRUCTURAL MODEL

The numerical modelling of the groundwater flow in the western Dead Sea escarpment is based on the scientific open source software OpenGeoSys. OGS does not have the functionality to create a structural model. Therefore two methods come into consideration (Table 1): (1) Develop a structural model on the basis of borehole data using the well known and robust Ground Water Modelling software GMS and export the 3D model via 3dm-file to OGS. Or (2) interpolate the combined data from boreholes stratigraphy, digitalized geological maps, geological cross-sections and geological data tables in ArcGIS and export the resulting layers as Raster-files to OGS. At the beginning all available geological data, such as cross-sections, digital geological database and lithological data were digitalized in GMS. In Fig. 2(a) the generated 3D GMS model shows a good correlation with the geological map (1:200 000). Because of the target high accuracy of GMS it was not possible to export directly to the scientific software OpenGeoSys via 3dm-file, so the second method (ArcGIS/OGS), was used. In ArcGIS it was possible to use all available information of borehole data, geological cross-sections, virtual boreholes and geological data tables and to transform them via the kriging interpolation method in geological layers of the whole study domain. The results of the interpolation are saved as shape and ASCII-files (includes the z-information for each geological layer) (Sun *et al*., 2011).

The checking of accuracy of the interpolated layers of the structural model was done using ArcScene (avoid intersection between geological layers). The reviewed shape-files (including the geometry of the study area, i.e. border, well locations, wadis) and the Raster-files (asc-files) for each geological layer have been imported to OGS. The shape-files were converted to OGS-gli-files

Borehole data analysis method: GMS

Combined geological data analyse method: ArcGIS/OGS



+ robust and well known software for hydrogeological models, stable 3D model
– limit in data base for export as 3dm-file

+ varied data formats of input data, no limit in data base and exporting files
– complex data pre-processing for the 3D model of OGS

Fig. 2 Two different methods to create a 3D structural model.

and the imported raster-files were transformed via the mesh-generator GMSH (Geuzaine & Remacle, 2009). The 3D model was generated by inserting Steiner points and using a Quadtree algorithm described in De Berg *et al*. (1997).

The result was a very precise 3D-layer structural model (Fig. 2(b)) with good mesh quality (Rink *et al*., 2011), which includes the information of node geometry, element topology and material groups. The final numerical model consists of 184 481 elements and 114 327 nodes, representing a total of 55 hydrogeological units (Rink *et al*., 2011).

GROUNDWATER FLOW MODEL

The structural model is the base of the numerical groundwater flow model. As starting conditions physical and chemical properties of fluid and solid phase were set as well as the material properties representing the geological formations.

The following hydraulically system condition has been assigned (Fig. 3):

– subsurface catchment → no flow boundary conditions at the northern, western and southern border of the study area.
– flow boundary condition at the eastern border of the study area which is at the same time the groundwater outflow to the Dead Sea.
– constant head boundary along the Dead Sea (= water level of the Dead Sea).
– for some models: constant head (water level) boundary condition with some of the water wells.
– groundwater recharge.
– water abstraction of pumping wells as a flux-boundary condition.

The simulation of the steady state model is based on the estimation of groundwater recharge by Guttman (2000). Afterwards it is possible to calculate approximately the recharge from the distribution of precipitation and evapotranspiration (Weiss, 2007). For the parameterisation of the geological layers the hydraulic conductivity of the aquifers and aquicludes was specified as material groups. Finally the output data for each time step of the groundwater flow process were saved as tec- or vtk-files and can be visualised using ParaView, TecPlot or OGS data explorer (Rink *et al*., 2012).

RESULTS

Because of complicated geological structure and low amount of calibration data the simulation procedure of the numerical groundwater flow model starts with very simple assumptions. At the beginning different amounts of groundwater recharge (Fig. 3(a)) were defined and hydraulic properties of the aquifer/aquiclude system were constant. Later the groundwater recharge was set constant and the hydraulic properties are selectable.

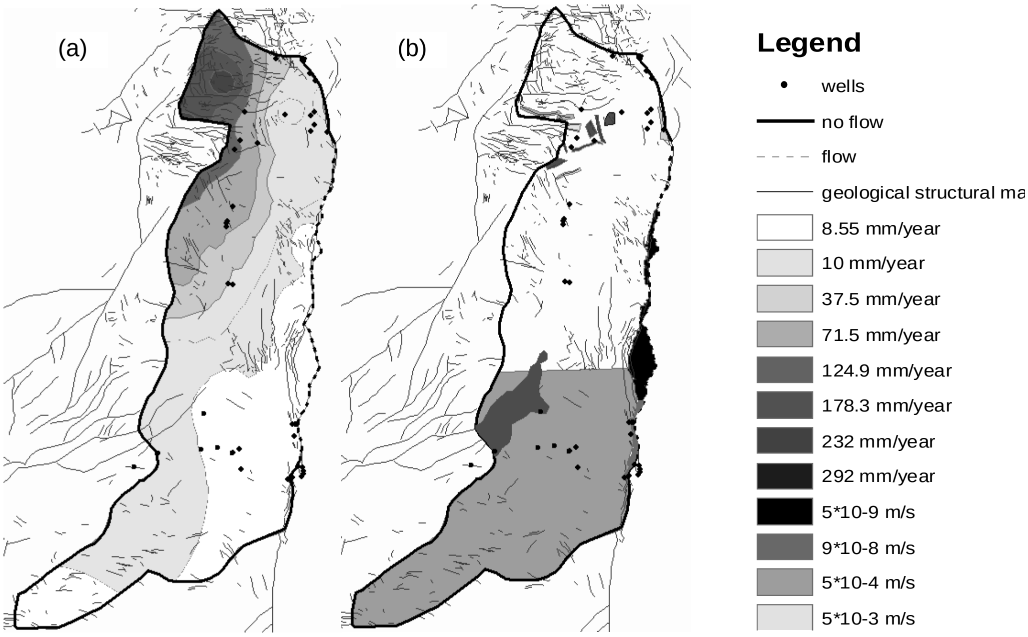


Fig. 3 Spatial distribution of groundwater recharge (a), refinement of hydraulic conductivity in selected areas (b).

The first models contain the four layer concept (bottom to top: lower aquifer/aquiclude/upper aquifer/aquitard). The first run used a constant amount of recharge over the study area. The simulation results could not represent the steep gradient in water level in flow direction from observed water wells. The next model scenarios use the distributed recharge only over outcropping aquifers. But the simulated water heads were also not able to achieve the measured water levels. In the third model the recharge was depending on the distribution of annual amount of precipitation (Guttman, 2000). In general the model simulation calculated water levels considerably lower than expected, except in regions close to the Dead Sea (Kalia). Conclusions of the first runs were constant groundwater recharge distribution after Guttman and variable hydraulic conductivity. Therefore the hydraulic conductivities were changed (Fig. 3(b)), to begin with over huge areas, and in a second phase along anticlinal to synclinal structures. The simulation results were not able to reflect the measured groundwater levels well. The hydraulic gradient was too big and all water flowed directly into the Dead Sea without a time delay. This resulted in a spatial adjustment of the hydraulic conductivity of the Quaternary sediments along the Dead Sea. The Quaternary sediments in the structural model have kf-values of 5×10^{-9} m/s, which should retain the water in the middle part of the study area. The next model runs confirmed this assumption. In the following runs some geological and tectonic information about N–S oriented faults (e.g. around Jerusalem and Kalia2) was integrated into the model. The results show a good correlation between measured and simulated water levels in the northern and eastern part of the research area (see Fig. 4).The next task was to achieve better simulation results for the southern part of the catchment area around the town of Arad. The approach was to hold the calibrated conditions (kf-value and groundwater recharge) in the northern part constant and change only the parameter of hydraulic conductivities in the southern part and in a previously closed area of Quaternary sediments along the Dead Sea. These changes lead to a small decline in the water levels of the Arad wells, but also influence the northern part. In the next model phase the interaction was stopped by the parameterisation of the basin structure in the north of the Arad wells with lower kf-values (9 × 10^{-8} m/s). This step only leads to a small decline in the Arad wells. The wells still have too much water, with a difference of between 60 and 200 m to measured water levels. Further adaption of geological structures should lead to better results in the southern part in the future.

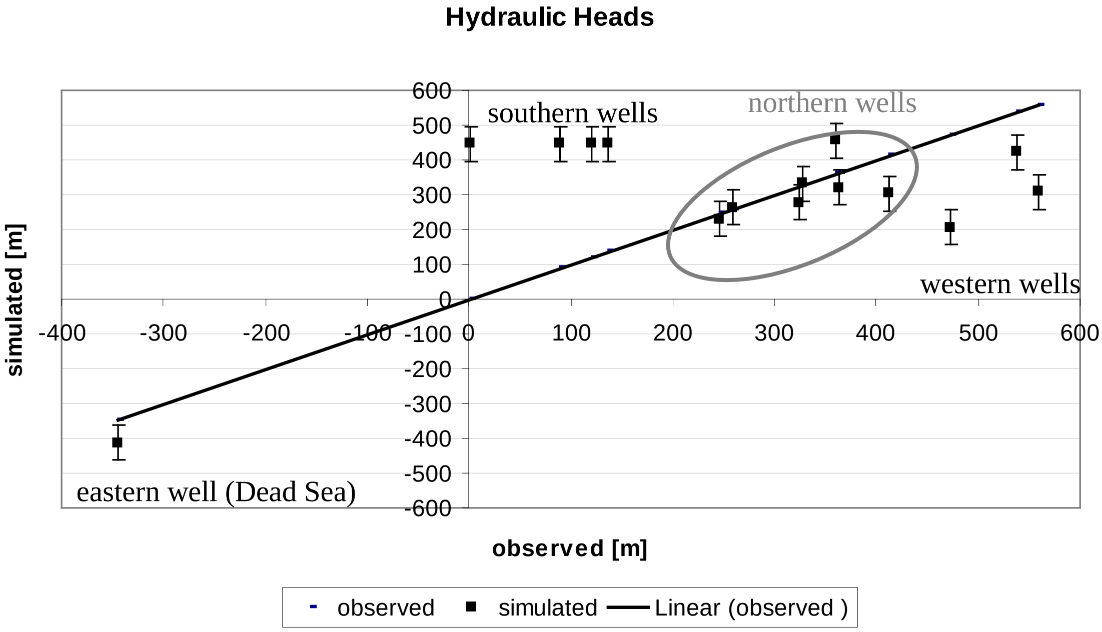


Fig. 4 Model results (comparison of observed to simulated water levels) with focus to spatial well accumulation.

CONCLUSIONS AND FUTURE WORK

With this study we presented a geometrically complex 3D structural model of the heterogeneous geology of the Turonian-Cenomanian Aquifer system, which is the basis for the numerical groundwater flow model of the western Dead Sea escarpment. The calibration of the groundwater flow model still has some uncertainties due to the complicated geological structure, and the limited number of boreholes and hydrogeological information in existence. The recent models showed good results for the northern and eastern part of the model area, while the simulated water level of the western and southern wells could not achieve the measured water levels. So the numerical groundwater flow model was able to represent the hydraulic conditions in the northern and eastern part of the aquifer system. Afterwards, during calibration of the southern wells, the water level of the northern and western part was also affected. So we proposed that a hydrogeological barrier between the northern and southern part is reasonable to cut the connection between the northern and southern parts and to reach successful calibration results. As a second hypothesis we propose that the hydraulic conductivity along the NW–SE fault next to the western faults has to be adjusted. In general, to overcome these problems of accuracy we have to focus more on regional scale (e.g. wadi-catchments) to understand the groundwater flow in more detail. The next step is the set-up of the transient groundwater flow model. Therefore we will use the hydrological model JAMS (Jena Adaptable Modelling system; Krause, 2001) which simulates the time-dependent groundwater recharge based on hydrological responses units (HRU-concept).

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REFERENCES

De Berg, M., Cheong, O., van Kreveld, M. & Overmars, M. (2008) *Computational Geometry: Algorithms and Applications*, third edn. Springer-Verlag, Heidelberg.

Flexer, A. & Yellin-Dror, A. (2009) In: *The Water of the Jordan Valley* (ed. by H. Hötzl, P. Möller & E. Rosenthal). Springer, New York.

Geuzaine, C. & Remacle, J.-F. (2009) Gmsh: a three-dimensional finite element mesh generator with built-in pre- and postprocessing facilities. *Int. J. Numerical Methods in Engineering* 79(11), 1309–1331.

Guttman, J. (2000) Multi-Lateral Project B: Hydrogeology of the Eastern Aquifer in the Judea Hills and Jordan Valley. *Mekorot Water Company, Report 468, p. 36*.

Krause, P. (2001) Das hydrologische Modellsystem J2000 – Beschreibung und Anwendung in großen Flussgebieten (The hydrological modelling system J2000 – Documentation and application in large river basins); Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment, Band 29, 2001.

Kronfeld, J. & Rosenthal, E. (1987) In a search of a characteristic signature for groundwater aquifers – a case study from Israel. Comment. *J. Hydrol.* 93, 149–164.

OGS (2011) OpenGeoSys Project. www.opengeosys.net.

Rink, K., Kalbacher, T. & Kolditz, O (2011) Visual data management for hydrological analysis. *Environ. Earth Sci.* doi: 10.1007/s12665-011-1230-6.

Rink, K., Fischer, T., Gräbe, A. & Kolditz, O (2012) Visual preparation of hydrological models. In: *Models – Repositories of Knowledge* (ed. by S. E. Oswald, O. Kolditz & S. Attinger), 113–118. Proceedings ModelCARE2011, Leipzig, Germany (this volume).

Sun, F., Shao, H., Kalbacher, T., Wang, W., Yang, Z., Huang, Z. & Kolditz O. (2011) Groundwater drawdown at Nankou site of Beijing Plain: model development and calibration. *Environ Earth Sci* doi: 10.1007/s12665-011-0957-4.

Weiss, M. & Gvirtzman, H. (2007) Estimating Ground Water Recharge using Flow Models of Perched Karstic Aquifers, doi: 10.1111/j.1745-6584.2007.00360.x.

Wu, Y., Toll, M., Wang, W., Sauter, M. & Kolditz, O (2011) Development of a 3D groundwater model based on scarce data: the Wadi Kafrein catchment/Jordan. *Environ. Earth Sci.* doi: 10.1007/s12665-010-0898-3.