Evaluating Remediation Potential of a Salinized Heterogeneous Aquifer System Using Three-Dimensional, Density-Dependent Groundwater Modeling

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ABSTRACT

This extended abstract shortly describes numerical modeling activities for a density-dependent groundwater model in a coastal arid region. The numerical modeling tool is benchmarked and used to calibrate the regional domain setup with its heterogeneous hydro-geology. Afterwards, the model is used to assess remediation potential of the local aquifer system. Results show that remediation actions will require a long-term strategy to retrieve the already salinized regions of the aquifer.

INTRODUCTION

This extended abstract presents a groundwater case study in the Al-Batinah, the northern coastal region of Oman. As in other arid regions, groundwater is the most reliable source for freshwater within the two catchments chosen for studying (wadis Ma'awil and Bani Kharus). Within this agriculturally used coastal region, where water consumption nowadays exceeds annual recharge, water table drawdown and subsequent saline intrusion are problems that need to be addressed in order to ensure sustainable water availability in terms of quality and quantity.

The work at hand shortly portrays modeling activities with respect to variable density flow in coastal areas and summarizes results of the case study. Relevant publications with more detailed information can be found for the development and application of the hydro-geological model (Walther et al 2012a), the regional groundwater model setup and steady state calibration (Walther et al 2012b), as well as for the transient calibration, water budgets and scenario simulation (Walther et al 2014, in review).

METHODS

Modeling Tools

To simulate groundwater flow and mass transport, the numerical modelling tool OpenGeoSys was utilized (OGS, Kolditz et al 2012; www.opengeosys.org). The numerical model is based on the Galerkin-FEM method. OGS was used before for several density-driven flow applications (Kalbacher et al 2011; Park and Aral 2008). Governing equations follow common standards for groundwater flow and mass transport in porous media and are given in Walther et al (2012b). Equation of state for density is a linear relationship which is reported to be sufficient for marine water density (Park 2004).

Benchmarking

To verify modeling capabilities of OGS for saltwater intrusion, the Goswami-Clement problem was used (Goswami and Clement 2007). The problem features a horizontally intruding and withdrawing saltwater front in an initially present freshwater environment. The conceptual model is depicted in Figure 1. For comparability reasons, the model setup and parameterization was followed as described by Goswami and Clement (2007). Exemplarily, Figure 2 compares results for the intruding case between experimental data and SEAWAT simulation output (by Goswami and Clement), and our own OGS simulations. All numerical results are in good accordance with experimental data.

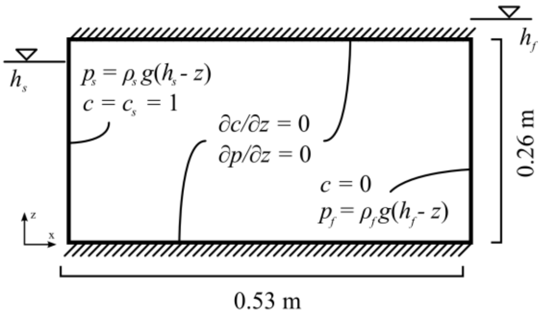

Figure 1 – Conceptual model of benchmark, from Walther et al (2014, in review), not to scale.

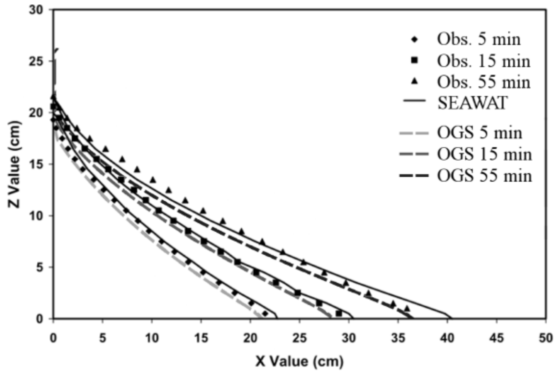

Figure 2 – Results for intruding state, from Walther et al (2014, in review).

Furthermore, Stoeckl et al (2014) compare results of several numerical models, among these OGS, to experimental data of development and degradation of a fresh water lens (see also Stoeckl and Houben 2012). Preliminary results show no significant deviations for either of the used models from the experimental data.

Regional Model Setup

The near coastal groundwater study area consists of a three-dimensional, heterogeneous aquifer with an extent of ca. 20·30 km^2 and a maximum depth of 450 m in the center of the domain ("Ma'awil trough"). The hydro-geological model mainly consists of twelve distinct material groups of different material properties (from gravel to clay). Above a less permeable secondary aquifer, a thin and highly permeable primary aquifer is present at the coast, increasing in depth to the south until the Ma'awil trough. The hydro-geological model is visualized in http://youtu.be/_jx0wt6Q1Ow.

Boundary conditions of the numerical model are upstream subsurface inflow from mountainous recharge regions, spatially distributed pumping abstraction near the coast, and given sea water level and salinity. More details on the characteristics of the study area and the setup of the hydro-geological and numerical model are described in Walther et al (2012b) figures 4, 6, 7 and table 3.

RESULTS

Pre-development and Active Pumping State

Before the 1970s, groundwater abstraction was primarily achieved through hand-dug wells, and the aquifer system was supposed to be in a steady state. Simulations for this pre-development state could be calibrated with high correlation (correlation coefficient R^2 = 0.83). When cultural changes and industrialization made modern pumping wells available to local farmers, water abstraction increased dramatically. Within this transient calibration time, i.e. 1974-2005, the correlation coefficient of groundwater levels reduced to $R^2 = 0.61$ until the year 2005. Deviations may result from several reasons, including low input data quality, or wide ranges of unknowns for calibration.

Simulation results for saline intrusion are similar to published measurement data concerning temporal development and spatial variability along the coast (Walther et al 2014, in review). A video (http://youtu.be/-xBQJ9WWPJY) shows the salinity distribution and flow paths through stream tracers originating in the southern and near coastal model domain exemplary for 1985. The effect of the heterogeneous permeability distribution can be recognized through the interlaced flow paths of the stream tracers that eventually merge into convection cells at the salt-freshwater interface.

Future Projection

In order to assess the remediation potential of the aquifer, a "best-case" scenario simulation was carried out with the assumption, that all pumping activity was ceased after year 2005. Additionally, we assume that the withdrawal of the saltwater will not involve any retention processes (e.g. reversible adsorption, double porosity continuum). The scenario simulation time was 500 years. We define the remediation potential Φ as

$$\Phi = 1 - c_{rel} \frac{\lambda}{\lambda_{max}} \quad \textbf{(1)}$$

with c_{rel} is relative concentration of salinity 10 m below groundwater level in 2005, λ is half-life of c_{rel} , and λ_{max} is maximum of λ. Comparable to the well-known half-life of a decaying element, the salinity half-life λ describes the time until the concentration of a mesh node reaches half of its value in the year 2005.

Figure 3 shows heterogeneous patterns of Φ. Some areas show a high remediation potential, while others do not reach half of the concentration value from 2005 after 500 years (striped areas). Differences between the eastern and western parts of the model domain are most likely due to a combination of spatially variable aquifer properties (e.g. permeability, yield) and corresponding preferred area of high abstraction activity. Although a "pump stop" might not be a practicable action, the best-case scenario simulation reveals a temporal dimension for remediation and overall salinization risk in the study area.

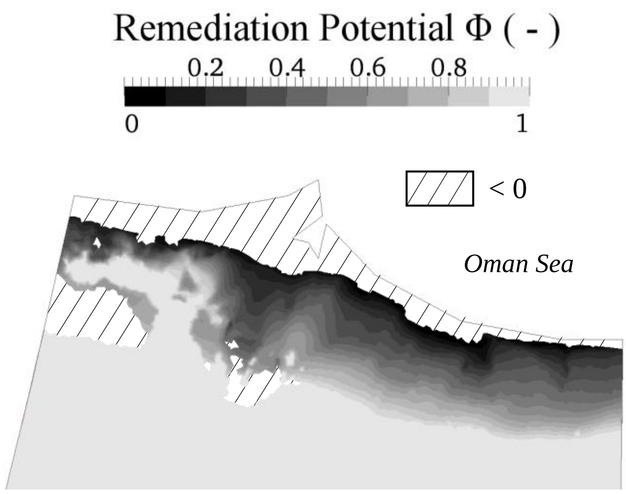

Figure 3 – Map of remediation potential in coastal area; from Walther et al (2014, in review).

CONCLUSIONS AND OUTLOOK

Although the data base was relatively weak compared to the typical requirements for this type of modeling including hydro-geological heterogeneities, the numerical model proved to be a useful tool. Calibrations show similar values as measurements and scenario results stress the vulnerability of the local aquifer system with its sensitive balance of the fresh-saltwater interface. In particular, the outcome underlines the necessity of an immediate action plan to prevent further saline intrusion or even total loss of the usability of the aquifer's groundwater resources.

ACKNOWLEDGEMENTS

The authors acknowledge the funding by the German Federal Ministry of Education and Research (BMBF Number: FKZ 02WM1166, IWAS), and by the Ministry of Science, Research and Arts of Baden-Württemberg (AZ Zu 33-721.3-2). The authors are grateful for the sincere cooperation of the Omani colleagues from the Ministry of Regional Municipalities and Water Resources, Muscat.

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