MedWater: Sustainable management of politically and economically highly relevant water resources in hydraulically, climatically and ecologically highly dynamic carbonate groundwater aquifers of the Mediterranean

Quantification of large-scale and long-term groundwater recharge and water resources in karst aquifers under Mediterranean climate: deterministic versus stochastic approaches.

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ABSTRACT

Carbonate aquifers generally are highly vulnerable with respect to water availability and quality. Some of the key questions therefore are: what is the available quantity of groundwater, how can it be assessed and how will the water resource develop in the long-term? Therefore, one of the primary MedWater objectives is the optimal management of groundwater resources in carbonate aquifers in the Mediterranean climatic region. Frequently, the respective aquifers extend for hundreds of square kilometres and are characterised by low data density. Process-based deterministic and stochastic approaches are employed to quantify the hydrological processes at regional scale. Comparing these different techniques will allow us to assess i) the impact and relevance of specific model parameters and processes, ii) the need to replicate the hydrogeological history within the model, and iii) the validity and practicality of each approach with respect to scale and data availability. Model results shall be transferred to other carbonate aquifers in the Mediterranean employing an empirical hydro-pedotransfer function (HPTF) for different types of land cover, climate, degrees of karstification, and thicknesses of the vadose zone. The application of HPTFs to Mediterranean karst aquifers will enable us to determine daily recharge rates, just requiring easily accessible input data such as precipitation and potential evaporation which can be estimated from remote sensing data. Finally, the RCP 4.5 climate projection is used for scenario analyses that consider global, economic, and policy changes. Condensed modelling results are linked to a "data-based decision-support system" (DSS) to assist stakeholders with their water resource management strategies.

INTRODUCTION

Climate research shows that the Mediterranean region will be one of the „hotspots" of the predicted shifts in climate and will be affected by increasing water scarcity in the near future (IPCC, 2012). Projected climate change is expected to have a significant impact on the availability of food and water and ecosystem services. The interaction between external factors such as climate change, population growth, and land use requires adaptation strategies that consider specifics of a region, a high degree of system knowledge and regional development goals.

Carbonate aquifers constitute an important water resource because of their wide geographical distribution, large catchments, and their focussed discharge at individual springs. However, their usability is restricted by their low storage capacity and high transmissivity, explaining also their high system dynamics. Semi-arid regions are characterized by a high temporal and spatial variability of precipitation and thus groundwater recharge. Key issues of sustainable groundwater management of karst aquifers under Mediterranean climate are therefore the assessment of groundwater recharge at local and regional spatial-scales and the response of the subsurface to short-term, high intensity storm events and longer drought periods.

The groundwater system selected for the principal study is the Western Mountain Aquifer (WMA), a transboundary aquifer between Israel and the Palestinian Territories, with a size of more than 9,000 km^2. It was developed since 1950 and constitutes an important resource for both countries. The WMA is recharged by rainfall in the outcrop region covering an area of 2,000 km^2, mainly located in the West-Bank area. Natural discharge occurs via two major springs, the Yarkon/Ras Al Ain and Taninim/Timsah spring. The hydraulic behaviour of the WMA is strongly influenced by highly permeable conduits. Karst elements of the WMA extend to large depths, even to depths of 1,800 m below ground level. However, the distribution, the type of karst features and therefore the response to recharge events is highly uncertain. Therefore, one of the goals of MedWater is to identify the **optimal modelling concept for such a highly dynamic and complex system and to develop new management tools that are suitable to be applied by stakeholder within region.**

METHODS

In order to predict the dynamic response of the aquifer system, comprising two compartments, a highly conductive, low storage conduit system and a low permeability high storage fissured aquifer matrix, the FE-code HydroGeoSphere (HGS) is used to simulate the coupled hydrological-hydrogeological system with a deterministic multi-continuum approach. HGS simultaneously simulates the unsaturated zone and groundwater flow. The surface-subsurface flow regimes are coupled via a first-order exchange term to account for diffuse and rapid direct recharge. This concept is expected to accurately represent the characteristics of the rock-soil landscape, local recharge along karst features, transmission losses of ephemeral streams (wadis), and erratic precipitation pattern. Due to the large number of hydraulic parameters simulation results are subjected to considerable parameter uncertainty. Therefore, the regression-based polynomial chaos expansion according to Miller et al. (2018) is used to approximate parameters and to reduce required number of simulations considerably.

The above technique is employed to investigate the relevant processes and their interaction. However, to consider more optimal parameter uncertainty and to take into account data scarcity a stochastic single-continuum modelling concept using the FD-code MODFLOW is developed. Here, the unsaturated zone is not simulated and also the exchange between high permeable conduits and matrix is neglected, which is acceptable for large time steps (e.g. 1 month) and for management applications.

The single-continuum model is parameterised with a stochastic prediction of the karst networks distribution using a new pseudo-genetic algorithm (Stochastic Karst Simulator SKS, Borghi, 2012). Parameterization and location of the karst features are defined with probability density functions (PDF). Based on the PDF-information, a karst conduit network is generated that connects recharge areas with discharge points. Locations of assumed individual karst conduits and the geometry of the karstified horizons, assessed based on geophysical borehole data, are used for parametrization (Figure 1).

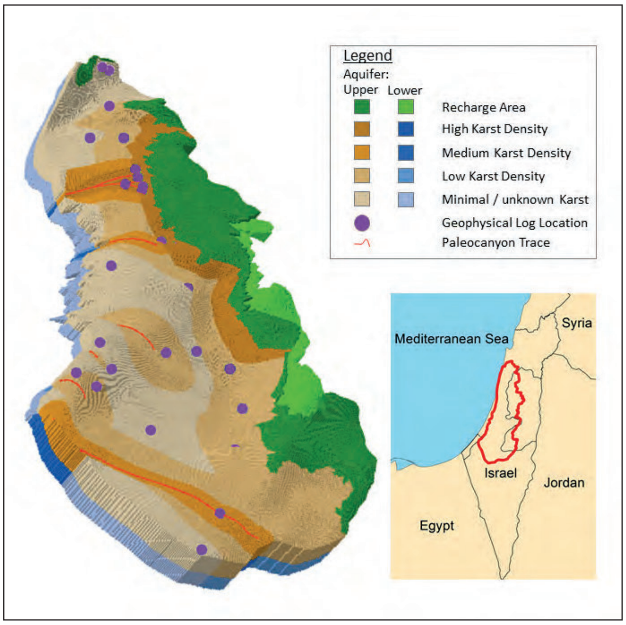

Figure 1: *Numerical Groundwater model and key karst features implemented into the stochastic modelling concept*

Both numerical flow models are calibrated using an inversion of time series of piezometric pressure heads and spring discharge measured between 1951 – 2006.

Both numerical approaches require a quantification of groundwater recharge. The management of the groundwater resource relies on an appropriate estimation of recharge that captures the influence of the unsaturated zone, semi-arid climatic conditions, extreme precipitation events, and periods with high draught intensity on the recharge total as well as its temporal distribution. In the HGS-model model groundwater the recharge distribution is directly simulated, while the stochastic model requires an external recharge calculation as source term.

Calculation of recharge is based on i) a spectral analysis (SA) and ii) on the development of a Hydro-Pedotransfer function

(HPTF). The SA consists of a cross-spectral analysis and compares input and output time series of the karst system, precipitation and spring discharge, respectively. Then the relation between input and output is examined and a transfer function (TF) is derived that represents the entire karst system behaviour and its hydrological characteristics using a set of lumped parameters. Our SA analyses spring discharge of a sub-catchment of the Eastern Mountain Aquifer (EMA) because high-resolution long-term data are only available for this region. The Hydro-Pedotransfer function (HPTF) calculates water fluxes in the unsaturated zone for synthetic scenarios considering variations in climate, land cover, soil type, degree of karstification, epikarst thickness, and depth of the groundwater table. Setting the percolation rate into correlation with the boundary conditions of the synthetic scenarios, the HPTF is derived with a non-linear multiple regression analysis. Data from remote sensing is employed to apply the HPTF for other Mediterranean karst aquifers.

Finally, using simulation of regional climate projections (scenario RCP 4.5) for Israel until 2071 (Hochman et al, 2018) scenarios are calculated considering predicted water demand based on population growth and changes in agriculture, industry, and land use.

FIRST RESULTS AND DISCUSSION

For the design of the karst network it is necessary to reconstruct the karst-genetic development. Carbonate rocks of the WMA were folded during the Oligocene into several NNE-SSW-trending anticlines (Bar et al., 2008). Subsequent erosion of these anticlines resulted in today's recharge areas in the Judean Mountains. Major changes in sea-level, especially during the Messinian Salinity Crisis, drove the formation of deep, multi-layer karst conduit systems (Laskow et al. 2011). Vertical distribution of conduits was controlled by i) the sea-level changes and consequently ii) the depths of new canyons draining the entire catchment. Especially within the coastal plain highly permeable karst was developed, explaining the low South-North trending hydraulic gradient. Karst conduits also cross the aquitard connecting Upper and Lower Aquifer. Our numerical model consists of 3 layers, representing the Upper and Lower sub-aquifers of the WMA, which are confined close to the coastal plain. The Hydrological Service of Israel (HSI) provided GIS-data of the geology of aquifer horizons and the outcrop area. Further data of the aquifer geometry are taken from Abusaada & Sauter (2012). Currently, the HSI manages groundwater abstraction based on 3 regional aquifer management "cells". For these cells average groundwater levels and therefore available resources are calculated that form the basis of future pumping rate. Further geophysical and geological borehole data are provi-ded by the Geophysical Research Institute of Israel and MEKOROT. Climatic data, such as temperature, precipitation, wind speed, humidity, and evaporation are provided by the Meteorological Service of Israel. In the future additional data of soil moisture and spring discharge will be collected. Spring discharge is available for some Eastern Aquifer catchments (Auja, Ein Sultan) since the 1960s and since 2008 at high temporal resolution, the basis for the SA analysis.

The deterministic model is parameterized into discrete parameter zones. Hydraulic conductivity, specific storage coefficients of the fissured matrix and conduit, respectively, are defined according to literature values with increasing hydraulic conductivities towards the springs. For the stochastic model a karst genesis model generates a 3-D karst probability field. The different degrees of karstification are converted into hydraulic parameter fields. This process will result in a catalogue of groundwater models representing different types of karst aquifers. The ensemble of different models generates a range of equally probable results. Detailed information on the geology and the karst aquifer genesis will assist in the selection of the most likely groundwater model. The stochastic concept is suitable to parameterize large-scale systems with only a limited number of data available and depends less on the avail-

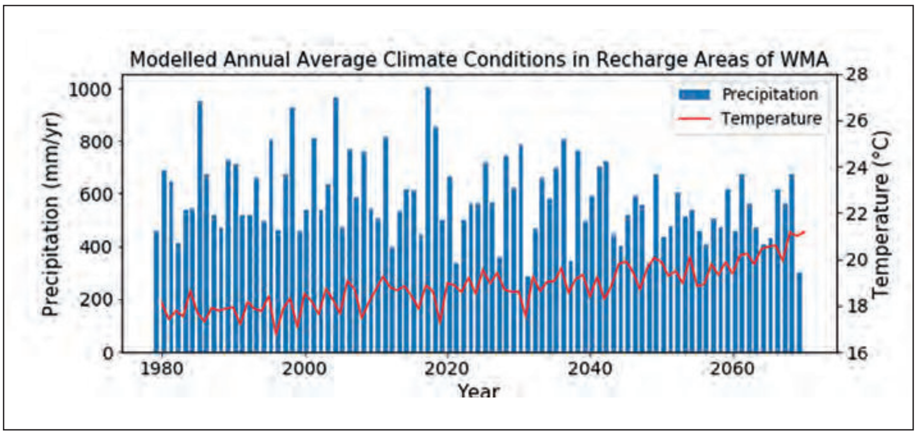

Figure 2: Predicted shifts in climate for the recharge area based on daily simulated precipitation and temperature of a regional climate model over Israel.

ability of high-quality observation time series. However, our deterministic model has the advantage of simulating the event-driven temporal pattern neglected by the single-continuum model which is matched less appropriate with the stochastic approach.

The response of the aquifer to changes in climate and socio-economic conditions is analysed by forward modelling. Climate data from a high-resolution (~8 km grid) regional climate model (Hochman et al., 2018) for 2041-2070 show that during winter mean temperatures will rise in the recharge area by up to 2°C, and that total precipitation depth will decrease by up to 20% (Figure 2). Climate modelling indicates that a larger proportion of rainfall will precipitate during extreme events with an increase of 10% in the Northern recharge area. However, this trend is not reflected in other parts of the recharge area.

Three socio-economic scenarios are defined: the "Trend" scenario updates the current trends in land use and water management, a steadily increasing population and moderate increase in imports of food/virtual water. The "Nature Conservation" scenario considers a drive towards more sustainable land use, a lower rate of population growth, and a strong increase in imports of food/virtual water (requiring less water to be abstracted locally). The "Economy" scenario includes maximal land use, but also maximal and efficient development of water resources (seawater desalination, artificial groundwater recharge). For this final scenario, imports of food would be reduced, requiring more locally produced water to be used for agriculture. A more dramatic population increase is included. The model results of the scenario simulations constitute the basis for the DSS. The DSS consists of three interlinked components: (1) an import routine to convert model results and configuration files into the DSS data environment, (2) a control environment to change the configuration files, and (3) a graphical user interface (GUI) to visualize the modelling results. Specific input files and scenario results can be requested and visualized by a browser based DSS client. Additionally, the DSS allows the user to change pumping rates or to add wells independently. The visualization of the results provides grid cell based information heads and total water budget as well as sustainable yield for specific times and locations as a basis for decision making by the stakeholder.

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MedWater

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