Assessment of groundwater recharge processes in a carbonate aquifer under semi-arid climate by an integrated surface-subsurface, multi-continuum model

Lysander Bresinsky[1], Jannes Kordilla[1], Martin Sauter[1]

[1]University of Goettingen, Dept. of Applied Geology, Germany <lbresin@gwdg.de>

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I. Introduction

Motivation

- Karst groundwater resources constitute a major freshwater resource in the Mediterranean.
- Mediterranean groundwater resources are likely to decrease due to a projected increase in temperature and the change in temporal precipitation patterns.
- Quantitative approaches, such as flow and transport modelling, are crucial tools for a sustainable aquifer management.
- Karstic rocks are subject to highly non-linear and rapid flow processes (i.e. preferential flow), making it nearly impossible to find an adequate single REV.
- Recharge estimations based on a correlation of cumulative annual or monthly precipitation and recharge do not consider temporal patterns and rainfall intensity.

Key Objectives:

- Estimate groundwater recharge based on a rigorous implementation of the surface-hydrological processes, that accounts for:
  - the particularities of rock-soil landscape,
  - focused recharge along karst features (i.e. sinkholes),
  - transmission losses of ephemeral streams (wadis),
  - specific climate conditions as well as the different precipitation patterns.
- Simulation of the effect of infiltration through a thick (several hundreds of meters) vadose zone on groundwater flow dynamics.

II. Area of study

- The study is conducted for the Western Mountain Aquifer (WMA), located in Israel and the Palestinian territories (see Fig. 2)

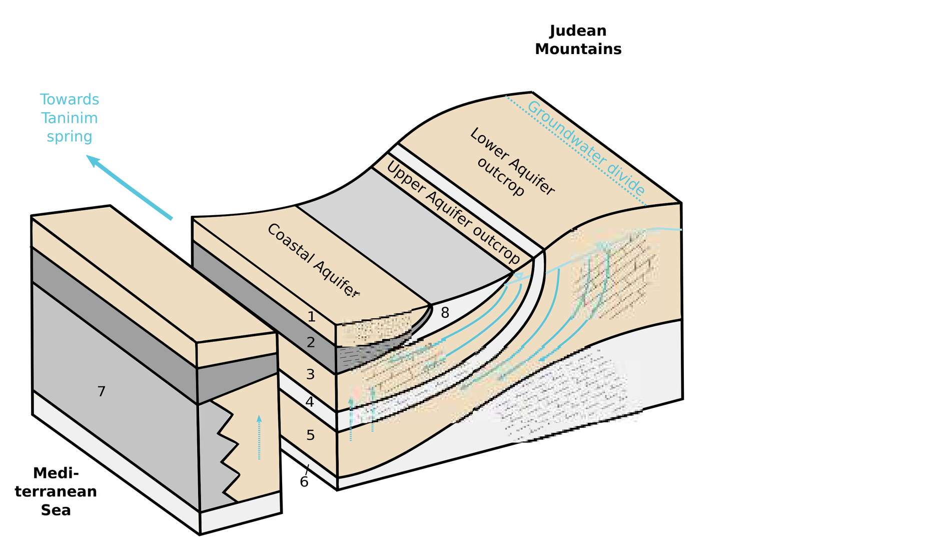

Figure 1: Schematic representation of the hydrogeological setting (after Weinberger, 1994); 1) Pleistocene Aquifer, 2) Saqiye Aquiclude, 3) Upper Aquifer, 4) Aquitard, 5) Lower Aquifer, 6) Lower Cretaceous Aquiclude, 7) Talme Yafe Group, 8) Eocene & Senonian Aquitard.

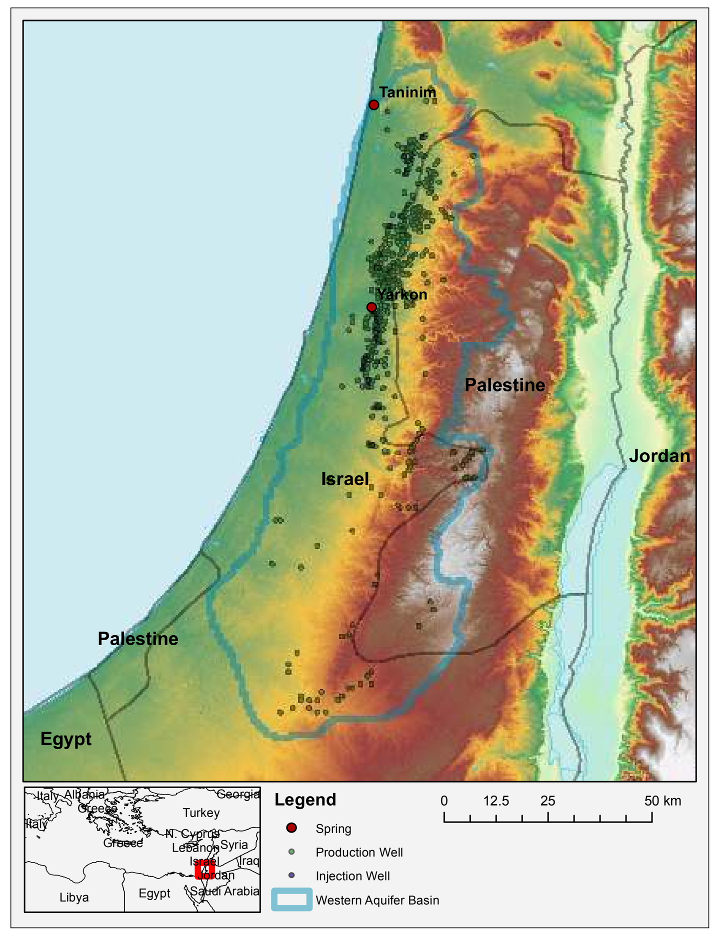

Figure 2: Catchment of the Western Mountain Aquifer.

Geological and hydrogeological setting

- The WMA is a highly karstic and fractured Cretaceous carbonate aquifer (mainly calcite and dolomite)
- Composed of two sub-aquifers (Upper & Lower Judean Aquifer) divided by chalk and marl of the Moza Formation
- Unconfined in the East and confined in the West (see Fig. 1)
- The rocks of the WMA are exposed to the surface due to an anticline structure in the Judean and Samarian Mountains (East)
- The aquifer drains at the Yarkon (till the 70s) and Taninim springs (see Fig. 2)
- Interaction with saline water from the Mediterranean is largely not present due to the impermeable layers of the Talme Yafe Group.
- Rainfall occurs at a high annual and seasonal variability mainly from December to February.
- Since the 1960s heavy pumping constitutes a major discharge component, leading to a depletion of groundwater levels.

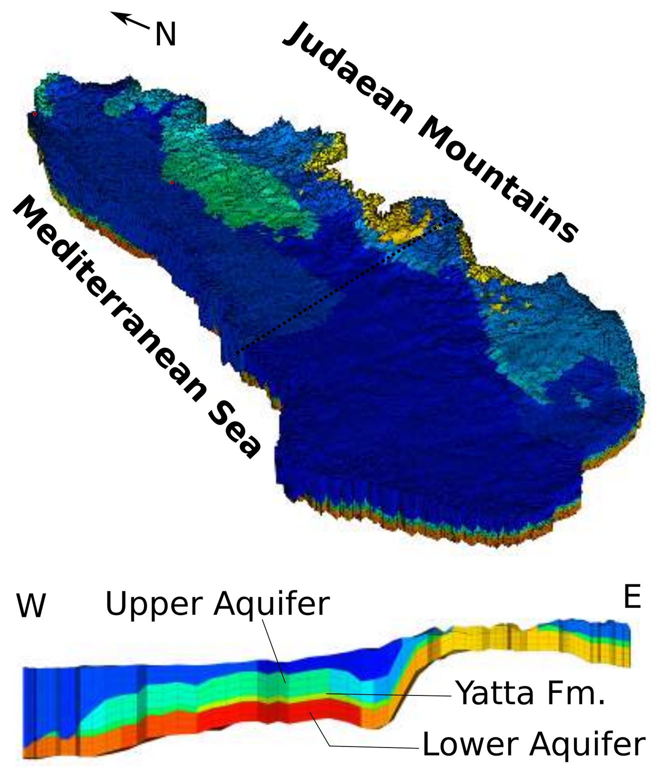

Figure 3: Discretization of the WMA model.

III. Methods

- The fully-integrated surface-subsurface and physically-based hydrogeological modeling tool HydroGeoSphere (HGS) is utilized on a high-performance-computing platform.
- HGS applies a modified form of the Richards' equation, which yields for the primary continuum (Aquanty, 2015):

$$-\nabla \cdot (w_m \boldsymbol{q}) + \sum \Gamma_{ex} \pm Q = w_m \frac{\partial}{\partial t}(\theta_s S_w), \quad (1)$$

and for the secondary continuum:

$$-\nabla \cdot (w_d \boldsymbol{q_d}) + \Gamma_d \pm Q_d = w_d \frac{\partial}{\partial t}(\theta_{sd} S_{wd}), \quad (2)$$

where the fluid flux q is respectively defined as:

$$\boldsymbol{q} = -\boldsymbol{K} \cdot k_r \nabla(\psi + z), \quad (3)$$

$$\boldsymbol{q_d} = -\boldsymbol{K_d} \cdot k_{rd} \nabla(\psi_d + z), \quad (4)$$

w: volumetric fraction of the total porosity occupied the continuum
q: fluid flux
K: hydraulic conductivity
z: elevation head
Q: volumetric fluid flux (boundary conditions)
θ_s: saturated water content
k_r: relative permeability
S_w: degree of water saturation ($S_w = \frac{\theta}{\theta_s}$)
Γ: exchange term
ψ: pressure head

- Exchange flow between the continua is realized via a Darcy-type exchange term:

$$\Gamma_d = \frac{\beta_d}{a^2} \gamma_w K_a k_{ra} (\psi_d - \psi) \quad (5)$$

β_d: geometrical shape factor
a: inter-continuum skin thickness
γ_w: empirical coefficient

- A simplified form of the Saint Venant equation accounts for surface flow:

$$-\nabla \cdot (d_o \boldsymbol{q_o}) - d_o \Gamma_o \pm Q_o = \frac{\partial \phi_o h_o}{\partial t}, \quad (6)$$

where the fluid flux $\boldsymbol{q_o}$ yields:

$$\boldsymbol{q_o} = -\boldsymbol{K_o} \cdot k_{ro} \nabla(d_o + z_o). \quad (7)$$

ϕ_o: surface flow domain porosity
h_0: water surface elevation
k_{ro}: horizontal conductance reduction from obstruction storage exclusion

- The coupling of the surface flow and the subsurface flow domain is realized via an exchange term, controlling the exchange flow r_o at the top nodes:

$$d_o \Gamma_o = w_m \frac{k_r K_{zz}}{l_{ex}} (h - h_o) + w_d \frac{k_{dr} K_{dzz}}{l_{ex}} (h_d - h_o) \quad (8)$$

h/h_d: subsurface porous medium/ dual medium heads
$k_r/k_d r$: relative permeability
K_{zz}/K_{dzz}: vertical saturated hydraulic conductivties (porous/dual media)

IV. Model calibration

- During the pre-development period the aquifer exclusively discharged via two springs (Yarkon & Taninim).
- The steady state simulation was configured to represent the water-level and discharge rate of the pre-development period (see Fig. 4).

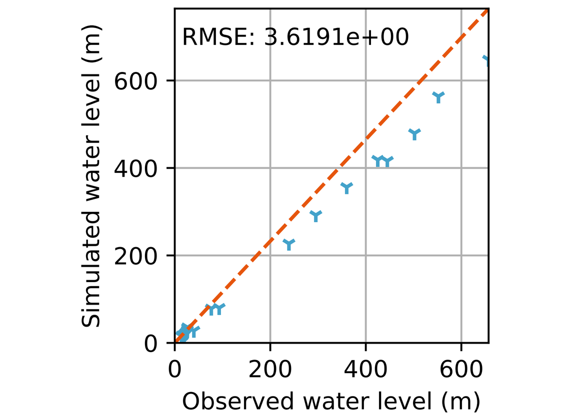

Figure 4: Computed vs. observed hydraulic heads for the entire basin

- The transient simulation within the period 09/15/2018 to 09/15/2007 reflects the observed spring discharge at the Taninim and Yarkon spring (see Fig. 5).
- The simulated discharge reproduces the drying up of the Yarkon spring in the 1970s

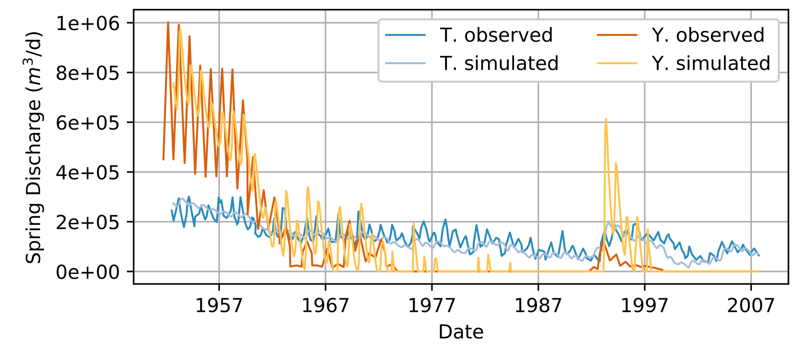

Figure 5: Computed vs. observed spring discharge

- In 1991/92 the Yarkon spring was reactivated due to an extremely wet year. The simulation replicates this event.

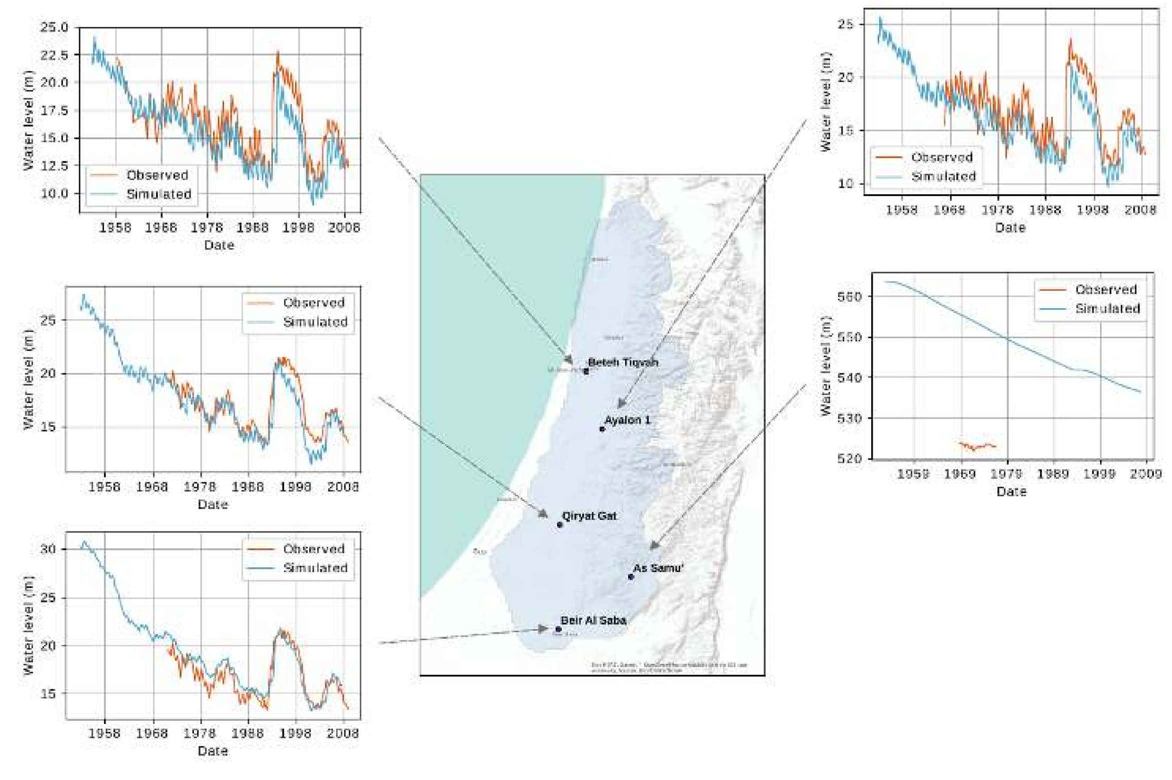

Figure 6: Computed vs. observed transient hydraulic heads

V. Conclusion & Outlook

Conclusion:

- A fully-coupled dual-continuum model of the subsurface and surface is expected to better represent the fast response to rain events accompanied by a high variability of flow rates, flow velocities and water level fluctuations.

Outlook:

- Definition of suitable unsaturated flow parameters (i.e. Van-Genuchten parametrization).
- Implementation of a 2D surface routing domain to account for transmission losses in ephemeral streams and focused recharge induced by karst landscape characteristics (i.e. dolines)
- Implementation of a second continuum to account for the duality of flow within karst.

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References:
Weinberger (1994): Journal of Hydrology **(161)**; Messerschmid (2018): Hydrological Processes **(32)**; Aquanty (2015): HGS User Manual - Theory