

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

## 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)

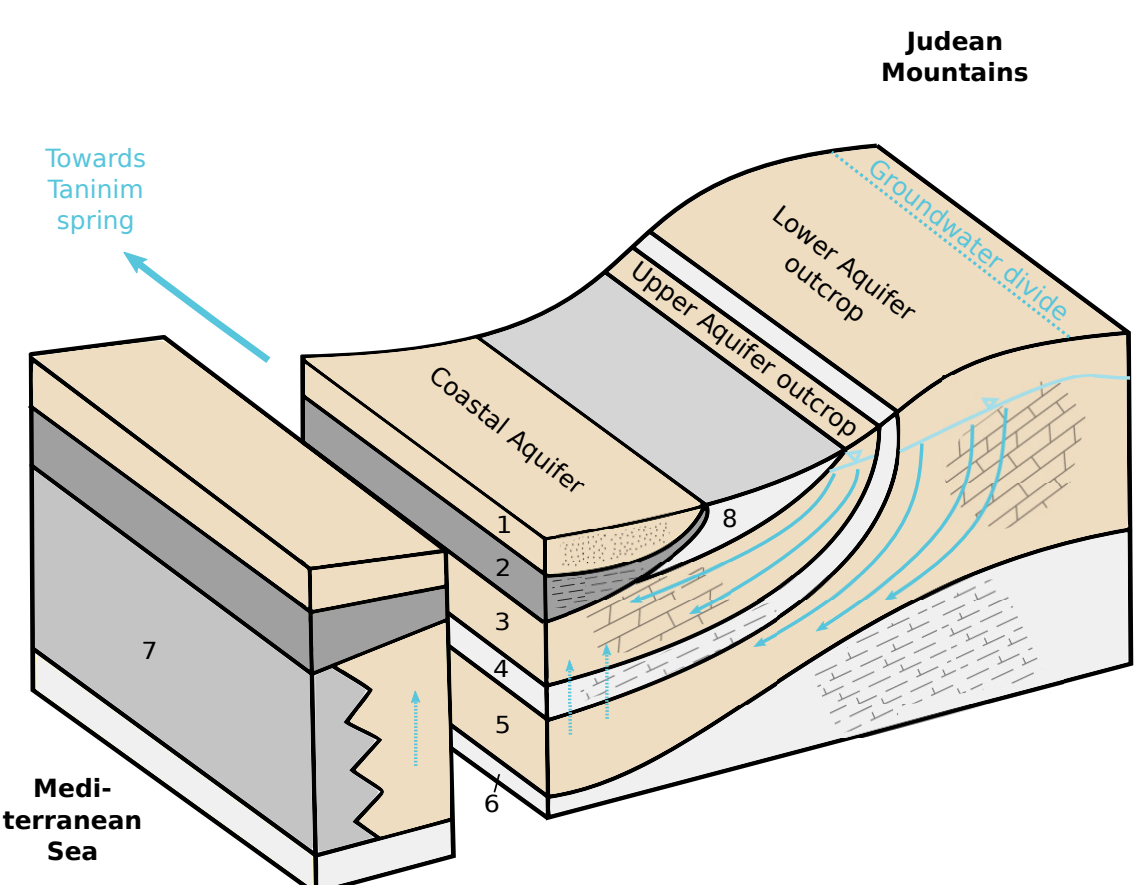


Figure 1: Schematic representation of the hydrogeological setting (after Weinberger, 1994); 1) Pleistocene Aquifer, 2) Saqiye Aquiclude, 3) Upper Aquifer, 4) Aquitard, 5) Lower Aquifer, 6) Lower Cretaceous Aquiclude, 7) Talme Yafe Group, 8) Eocene & Senonian Aquitard.

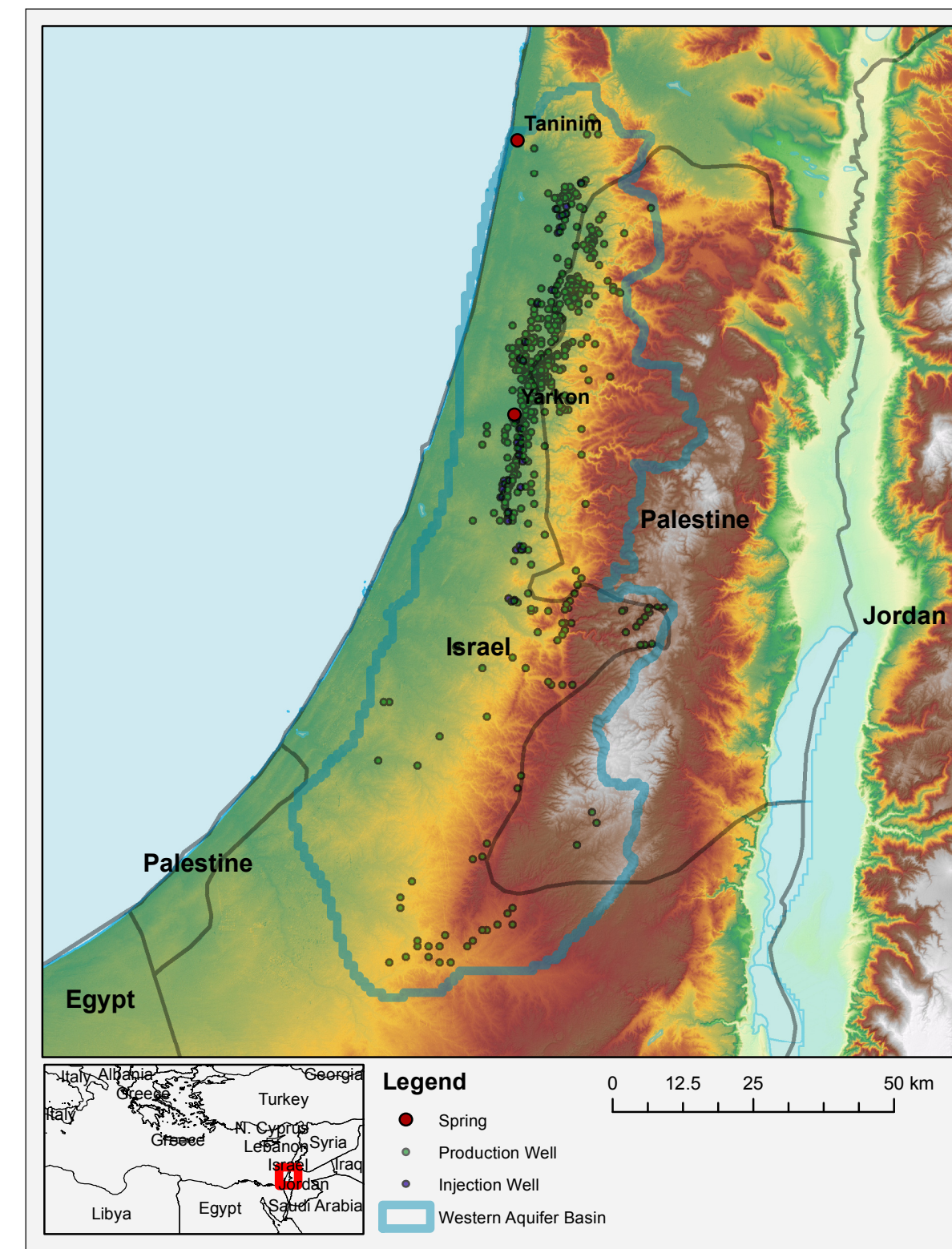


Figure 2: Catchment of the Western Mountain Aquifer.

- 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.

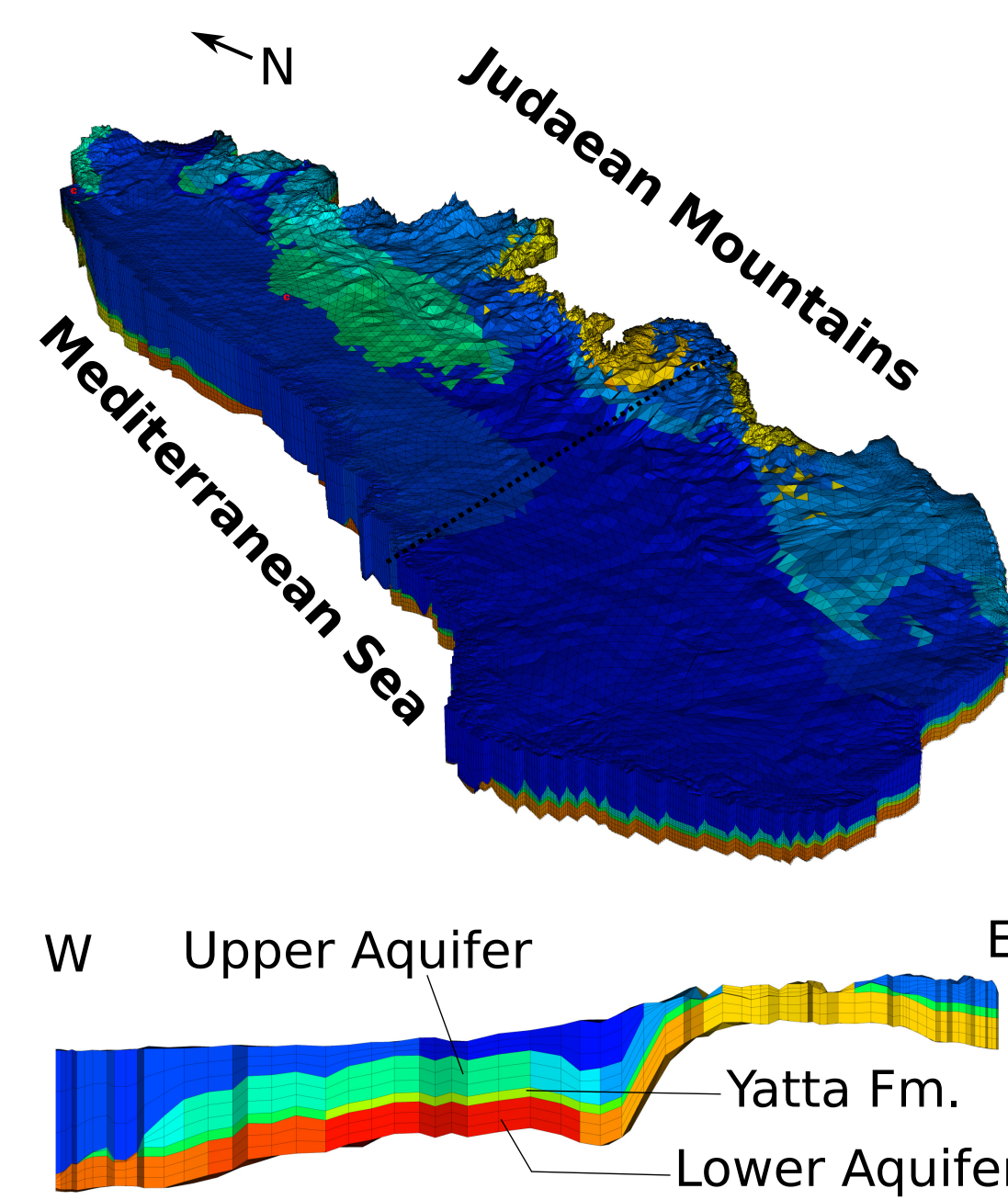


Figure 3: Discretization of the WMA model.

## 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):

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

### 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)

and for the secondary continuum:

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

where the fluid flux  $\mathbf{q}$  is respectively defined as:

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

$$\mathbf{q}_d = -\mathbf{K}_d \cdot k_{rd} \nabla (\psi_d + z), \quad (4)$$

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

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

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

$\beta_d$ : geometrical shape factor  
 $a$ : inter-continuum skin thickness  
 $\gamma_w$ : empirical coefficient

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

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

where the fluid flux  $\mathbf{q}_o$  yields:

$$\mathbf{q}_o = -\mathbf{K}_o \cdot k_{ro} \nabla (d_o + z_o). \quad (7)$$

$\phi_o$ : surface flow domain porosity  
 $h_o$ : 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  
 $k_r/k_{dr}$ : relative permeability  
 $K_{zz}/K_{dzz}$ : vertical saturated hydraulic conductivities (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).

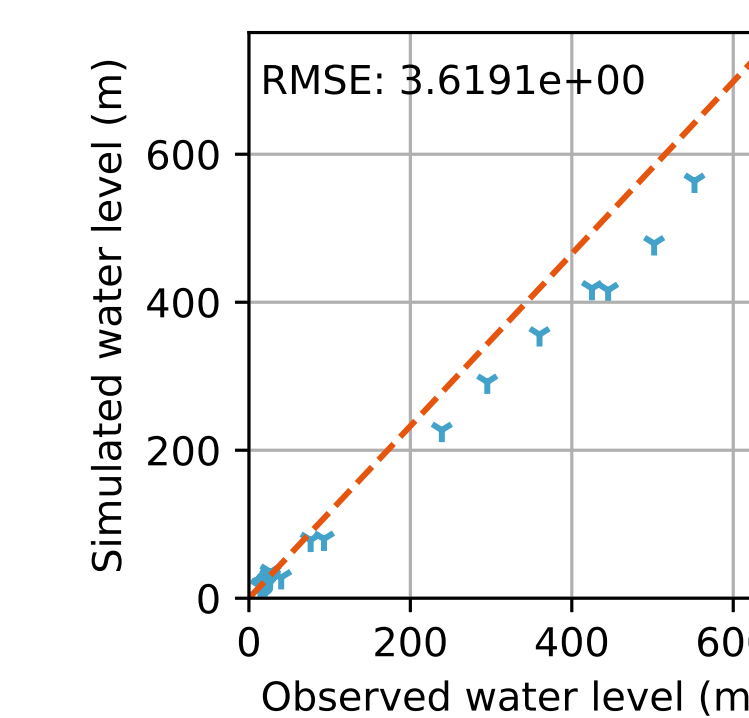


Figure 4: Computed vs. observed hydraulic heads for the entire basin

- 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

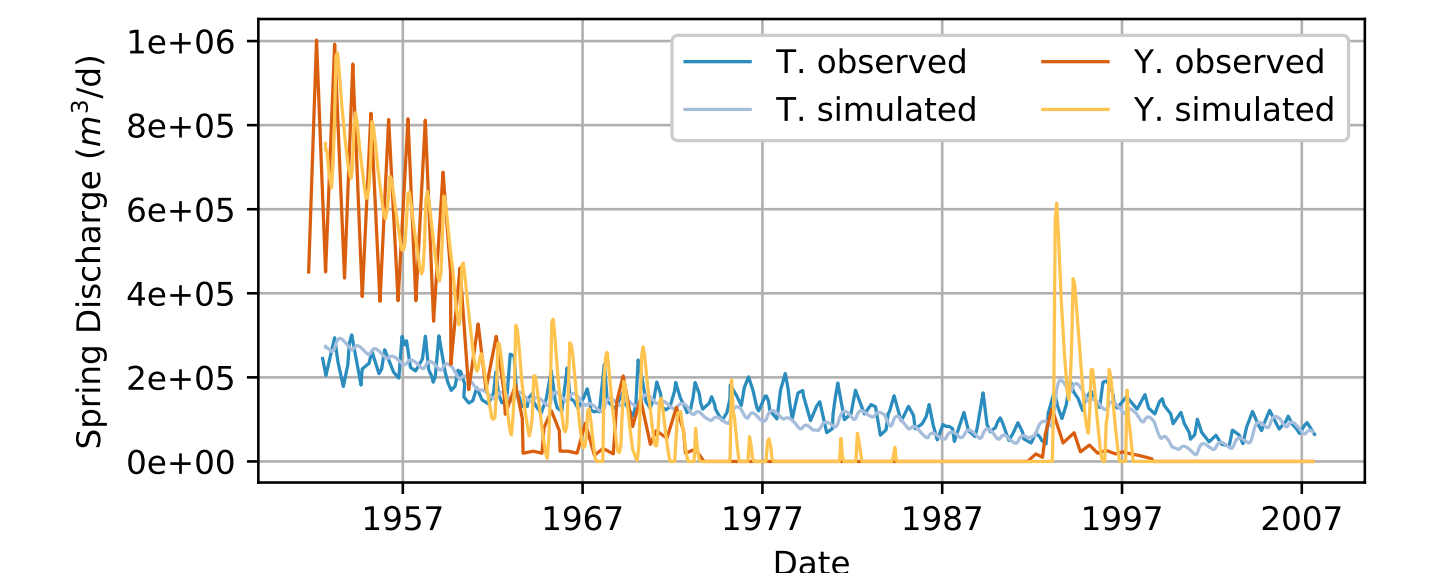


Figure 5: Computed vs. observed spring discharge

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

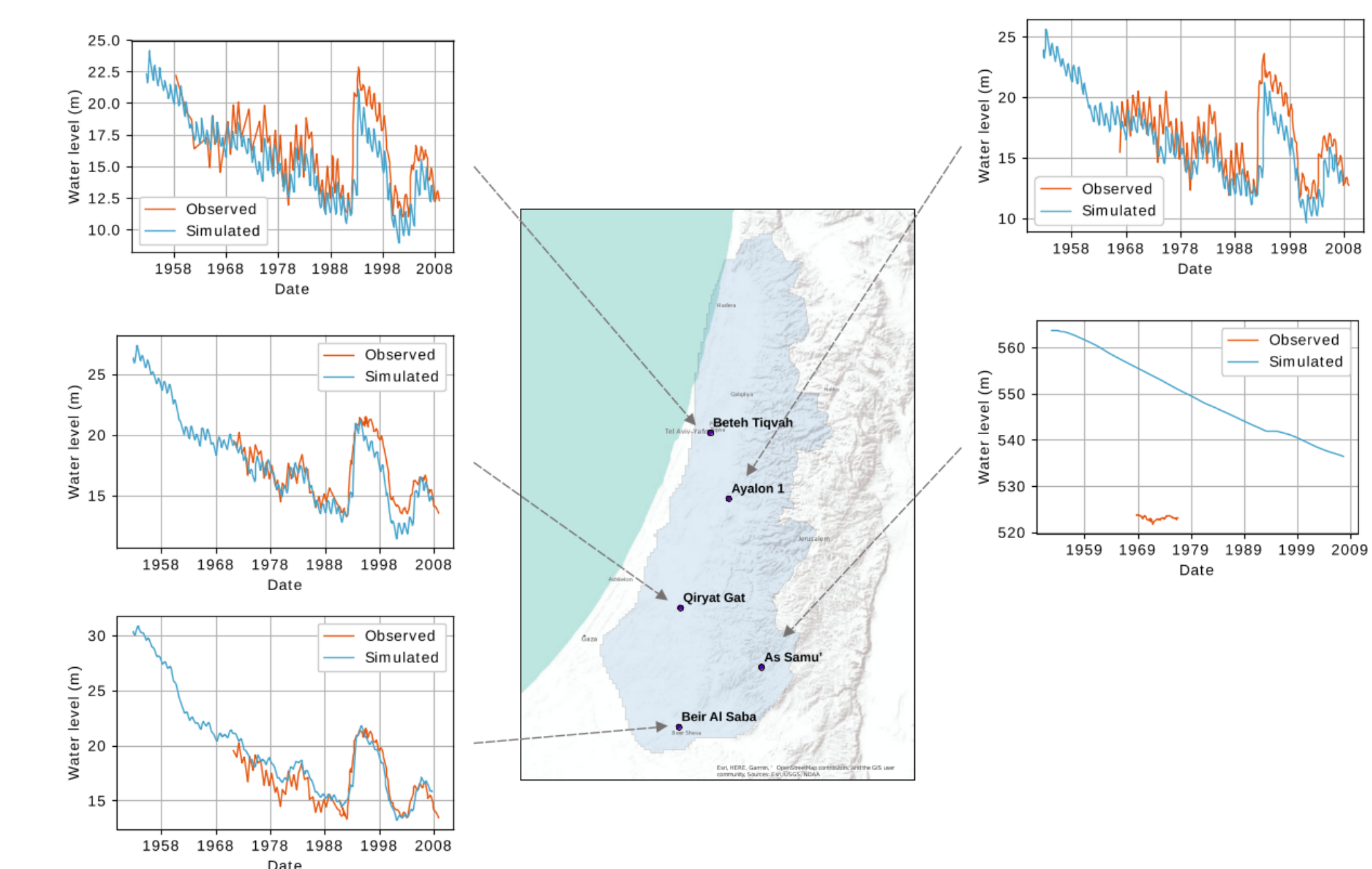


Figure 6: Computed vs. observed transient hydraulic heads

## 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.

### Acknowledgement:

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### References:

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