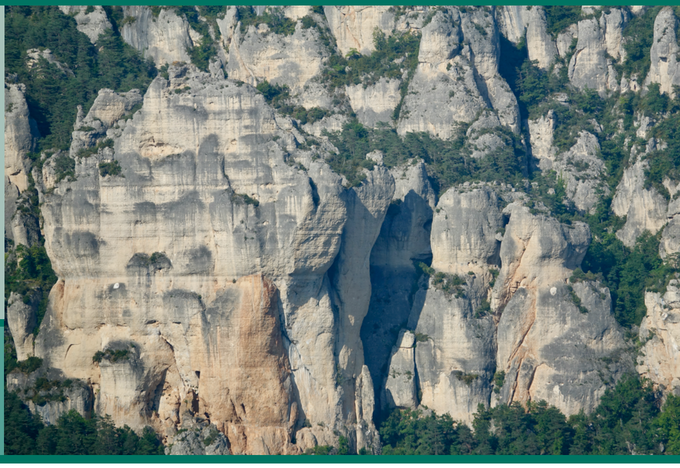

Comparison of modeling approaches for the simulation of surface and subsurface flow dynamics in complex fractured-porous karst aquifers

Key findings

- We compare two numerical flow models for the computation of groundwater storage dynamics to assess their ability to resolve the complex process spectrum and hence their specific predictive power with respect to available water resources.
- All numerical models are subject to a trade-off between predictive power and efforts to reduce parametric ambiguity and structural uncertainty.
- The appropriate level of model complexity is determined by the availability of field data and the type of problem to be solved, demanding different degrees of representation of hydro(geo)logical processes.
- In karst systems with thick vadose zones, it is important to include the flow processes in this compartment, since it can be an important resource particularly during drought periods.

Motivation

Flow dynamics in karst aquifers are subject to highly heterogeneous flow processes in all compartments, i.e., the surface, vadose, and phreatic zone (Figure 1). The heterogeneous distribution in hydraulic properties (e.g., hydraulic conductivity, storage) within these compartments affect the local and global routing dynamics and hence the magnitude and dissipation of the hydraulic signal between source (precipitation) and spring outlet (Jeannin & Sauter, 1998; Smart & Hobbs, 1986). Numerical models for the prediction of recharge and dynamics of groundwater resources are subject to a trade-off between predictive power and efforts to reduce parametric ambiguity and structural uncertainty. Here we compare two modeling approaches – a saturated single-continuum and a variably saturated dual-continuum flow model developed for the Western Mountain Aquifer in Israel and the West Bank – with respect to their fields of applications and their respective predictive power.

Methodology

The single-continuum model computes saturated flow based on the Darcy equation parameterized by volume and system (conduit / matrix) integrating hydraulic conductivities (Table 1), representing both the conduit and matrix flow compartment by a single parameter. The Upper and Lower Judaean Aquifer are discretized respectively by single-node layers, and the separating aquitard Moza/Beit-Meir is indirectly accounted for by pronounced anisotropic hydraulic conductivities in both sub-aquifers. The dual-continuum flow model for variably saturated water flows uses the Richards' equation for both continua with a vertically discretized vadose and phreatic zone. Both models utilize daily infiltration as an input computed a priori via a dual-medium water balance model representing recharge dynamics at the zero-flux plane below the soil zone. In the single-continuum model, infiltration is either computed by a soil water balance approach or as monthly recharge by a SWAT model. The single-continuum model directly routes the estimated infiltration to the phreatic zone, while the dual-continuum model computes variably saturated infiltration dynamics for both the matrix and karst conduits.

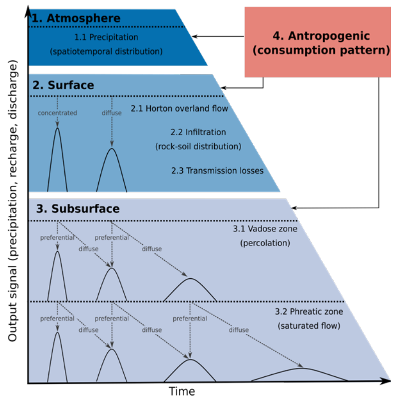

Figure 1: Overview of the flow compartments that affect local and global flow processes and provide storage

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Table 1: Comparison of the numerical models' physical representation and discretization

	Modflow (Single-Continuum)	HydroGeoSphere (Dual-Continuum)
	Physical process representation	
Surface routing	Coupled to a SWAT model with semi-distributed representation of infiltration excess based on Soil Conservation Service Curve Number (SCS-CN)	Distributed overland flow with depth-integrated Saint-Vénant equations*
Vadose zone (soil)		Soil water balance model including evapotranspiration dynamics
Vadose zone (consolidated)	Infiltration lag indirectly modelled via anisotropic hydraulic conductivity	Coupled dual-continuum system governed by the Richards' equation (Van Genuchten parametrization)
Phreatic zone	Darcy equation in a single-continuum setting	Coupled dual-continuum system governed by the Richards' equation (Van Genuchten parametrization)
	Discretization	
Temporal	Daily	Adaptive (daily-subdaily)
Spatial (vertical)	No vertical discretization, lumped representation of Upper and Lower Aquifer	Vertical discretization with adaptive resolution, sub-meter spacing close to surface, coarser resolution within the phreatic zone
Spatial (horizontal)	Quadrilateral mesh (total number of $\sim 5 \cdot 10^4$ cells)	Delaunay mesh with partially refined spacing (total number of $24 \cdot 10^4$ cells)
	Computational aspects	
Computational Effort	Low (~1h for a 20a simulation period)	High (~1.5d for a 20a simulation period)
Parallelization	-	OpenMP
	License and support	
Costs	Free	~2000€ (single-node license + technical support)
Support	No official support, rather large user community and forums	Technical support team of Aquanty, smaller user community

* not yet realized for the WMA model

Results

The models vary in terms of complexity and are subject to different degrees of uncertainty with respect to process representation and parametrization. Both models accurately simulate groundwater levels and spring discharge time series (i.e., the drying up of Yarkon spring desiccation) within the calibration period. However, each model has its distinct fields of applications and potential advantages and shortcomings. The single-continuum flow model runs much faster and requires far less computational resources. Due to the reduced number of processes involved and lumped representation of the vertical aquifer layer structure, the model is less vulnerable to parametric ambiguity. Therefore, it can quickly provide simulation results and can be embedded within a responsive decision support system to test the long-term effects of various pumping scenarios. However, the single-continuum model is subject to higher uncertainty (e.g., caused by the non-physical representation of the infiltration process) compared to the double-continuum model and therefore more likely prone to parameter degeneration (i.e., non-physical values). The unsaturated dual-domain storage capacity may vary significantly with time and space for aquifers with several-hundred-meters thick vadose zones. The superposition of rapid recharge via fractures and dissolution features (dolines, shafts) and long-term diffuse infiltration via the matrix domain must be considered, particularly in the light of the imminent changing precipitation patterns due to climate change. Further, the double-continuum model provides more realistic estimates of the global hydraulic parameters due to the lower structural uncertainty (at the expense of computational time). In contrast, the single-continuum model applies parameters with lumped physical representation (i.e., the low vertical hydraulic conductivity represents the Moza/Beit-Meir aquitard and the vadose zone).

Application

Due to their different strengths, both models have different fields of application. The single-continuum flow model finds its application in testing scenarios for groundwater flow on longer, i.e., monthly or annual time intervals, where mainly long-term storage processes are relevant. Should, however, short-term, event-based flow and flood problems be addressed, as well as transport problems for which flow velocities need to be better represented, single-continuum models are not the appropriate tool. In contrast, the double-continuum model can be applied to investigate the effect of the change in precipitation patterns concomitant with climate change and the role of the vadose zone for its storage dynamics. The double-continuum model can be expanded by integrating a surface flow continuum to account for Horton overland flow, improving the model's predictability regarding the partitioning of rainfall into infiltration and floods.

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