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A non-steady and non-uniform hybrid model for karst aquifer characterization

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Groundwater flow in karst aquifers is focused mainly in the highly permeable conduit drainage network. To investigate karst systems on local and regional scale, it is possible to interpret artificially induced signals, e.g. large scale pumping tests in a borehole intercepting a conduit in the vicinity of the spring. For a process-based interpretation of such pumping tests, it is necessary to consider the time and space dependent response of the hydraulic head in the karst conduit. Therefore, a model approach describing non-steady and non-uniform flow in karst conduits is a major challenge.

Hence, we adapted the U.S. Geological Survey code MODBRNCH (Swain & Wexler 1996), coupling a free-surface flow model with MODFLOW, to account for the specific flow dynamics in karst aquifers. The modified model ModBraC solves the St. Venant equations for open-channel flow. Modifications comprise mainly the implementation of a variable time step, the introduction of the Preissmann slot for pressurized flow (Zhang & Lerner 2000) as well as the adaptation of boundary conditions.

The model was evaluated with several benchmark tests: (1) pressurized flow, (2) changes between pressurized and non-pressurized flow, (3) unsteady and non-uniform wave propagation, (4) water transfer between the matrix and the conduits, and (5) karst hydraulics in a complex conduit network. These evaluation tests demonstrate the capability of ModBraC to account for karst hydraulics in coupled structures since the model results agree with those obtained from analytical solutions and other numerical models.

Model studies for a synthetic karst catchment, where a karst conduit drains the fractured porous rock matrix, were performed to test ModBraC for a more realistic situation. Therefore, flow in the karst system and the resulting spring discharges were simulated for several recharge events, where groundwater was directly routed through the conduit toward the spring. The initial filling grade of the conduit system was varied to investigate the resulting impact of fully and partially filled conduits. Results highlight that the signal transmission in partially filled conduits significantly differs from completely filled ones. Further, the transition from fully to partially filled conduits results in a characteristic stagnation of discharge during the dewatering of the conduits. The additional storage provided by the conduit volume is correctly considered by ModBraC, as reflected by the mass balance.

Finally, ModBraC can be considered as a well evaluated numerical approach to reflect the non-steady and non-uniform hydraulics in karst conduits. In contrast to steady and uniform hybrid models, ModBraC is able to account for the characteristic behavior of variably filled karst conduits. Therefore, we can conclude that the St. Venant equations are appropriate to describe flow in fully as well as in partially filled karst conduits and the hybrid model ModBraC can be used to describe the transient flow behavior of karst aquifers.

References:
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