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Coupled model of turbulent stream flow and hyporheic flow under varying hydraulic conditions

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The interaction between stream water, groundwater and the hyporheic zone is important for many hydrogeological processes and solute transport. In the hyporheic zone, where stream water mixes with groundwater, biogeochemical reactions and transformations occur and are responsible for self-cleaning mechanisms of stream systems.
The extent of the hyporheic zone and the residence time of the advectively transported solutes are mainly controlled by stream hydraulics, streambed morphology, ambient groundwater flow and the permeability of the aquifer and streambed material.
Numerical models that couple surface water with groundwater typically calculate exchange fluxes based on the hydraulic gradient between surface water and groundwater. However, for the assessment of total head in the stream typically only hydrostatic pressures are considered neglecting the influence of hydrodynamic effects on hyporheic exchange induced by turbulent surface water flow over structured beds. For instance, pool-riffle sequences are responsible for distinct variations in stream water levels and corresponding pressure distributions on the streambed, evoking relatively complex flow paths in the underlying hyporheic zone.
We present a three-dimensional modeling approach for coupling turbulent surface water flow with porous media flow, representing the hyporheic zone. The turbulent surface water flow is simulated with the open source computational fluid dynamics (CFD) software OpenFOAM, which solves the Navier-Stokes equations by the finite volume method. A two-phase (water and air) model approach is used to provide realistic flow simulations and stream water levels under both high and low stream discharges, respecting supercritical flow conditions ($Fr > 1$), e.g. hydraulic jumps. With the CFD software the pressure distribution on the streambed surface is derived. It serves as the upper head boundary condition for a flow and transport model of the hyporheic zone, which will be implemented in the reactive groundwater model MIN3P.
Our model domain is composed of sinusoidal three-dimensional pool-riffle sequences on a scale of about 10 m, representing a reasonable approximation of naturally occurring streambed morphologies. For surface water flow distinct steady state scenarios are performed, considering changing stream discharges and variations of the pool-riffle morphology by the amplitude-wavelength ratio. In the groundwater model, depending on the head conditions and the magnitude of groundwater in- or outflow, the flow in the hyporheic zone is simulated. Additionally, simulations of conservative and reactive transport in the hyporheic zone are conducted and heterogeneous aquifer material can be considered.
Hence, we are able to systematically evaluate how variations in surface water flow conditions due to hydraulics and morphology can influence and control the flow in the hyporheic zone under varying ambient groundwater flow.