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Modelling free surface aquifers to analyze the interaction between groundwater and sinuous streams

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Several mathematical methods for modelling free surface aquifers are available. Aquifer-stream interaction is an important application of these models, and are challenging to simulate because stream interaction is described by a highly variable head boundary, which can cause numerical instabilities and errors. In addition, when streams are sinuous, groundwater flow is truly 3-dimensional, with strong vertical flows and sharp changes in horizontal direction. Here 3 different approaches to simulating free surface aquifers are compared for simulating groundwater-stream interaction. The aim of the models was to investigate the effect of meander bends on the spatial and temporal variability of aquifer-stream interaction, and to develop a new 3D conceptual model of groundwater-stream interaction.

Three mathematical methods were tested, representing the three main methods available for modeling 3D unconfined aquifers: a saturated-unsaturated flow model, moving mesh, and a new coordinate transformation. The saturated/unsaturated model couples the saturated groundwater flow equation with a solution of Richards equation. The moving mesh solves the saturated groundwater equation with a free surface and deformable numerical finite element mesh. Finally, the new coordinate transform method employs a coordinate transform so that the saturated groundwater flow equation is solved on a fixed finite element mesh with a stationary free surface.

This paper describes in detail the new coordinate transform method. It employs a transformation of the vertical coordinate, so that the top surface remains stationary. The transformation introduces non-linearities into the saturated groundwater flow equation, with the hydraulic conductivity becoming a function of the head at the top boundary. Mathematical analysis is then applied to show well posedness, and provide stability and linear convergence results. Numerical results confirm the mathematical analysis.

The three methods were compared for a simplified 2-dimensional test case with highly variable stream flow boundaries. Results showed that all methods can properly simulate the groundwater head under steady-state and transient conditions. The coordinate transformation method was the least computationally demanding method, requiring 6 times less simulation time than the saturated-unsaturated and moving mesh flow models. The methods were then compared for a more challenging 3-dimensional problem. Results showed that the coordinate transformation method required 41 times less computational effort than the moving mesh.

The coordinate transformation method was then applied to simulate a field site located at Grindsted stream, Denmark. In order to investigate the importance of stream geometry for the problem, two scenarios were implemented: straight stream and a meandering stream. The model was compared to field data to verify results.

The model was shown to properly simulate groundwater head variability measured at piezometers and discharge to the stream as measured by heat flux, point velocity probes and flux meters. The results from the straight stream scenario and the meandering stream scenario showed that meander bends strongly affect groundwater-discharge to the stream: the discharge is focused at the outward pointing side of the meander bends. Similarly, the groundwater flow paths toward the stream are affected by the stream meanders. Shallow groundwater enters the meander from the outward-pointing side of the bend, while deep groundwater flows beneath the stream and enters the stream from the opposite side. On the basis of these results, a new three-dimensional conceptual model of groundwater-stream interaction is proposed. The new conceptual model demonstrates that conventional two-dimensional symmetric groundwater streamflow conceptual models do not apply for real meandering streams.