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Groundwater – surface water interaction at the catchment scale – case studies in the Meuse basin

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Abstract With numerous processes and uncertainties involved flow and transport simulation at the watershed scale represents a challenging research topic. Nevertheless it may prove to be indispensable for the prediction of impacts to humans from diffuse pollutant sources. In these case studies we focus on the first step: the flow part of a coupled process model for groundwater-surface water interaction. Study areas cover tributaries to the Meuse river within the Beerze-Reusel drainage basin (440 km^2) in the Netherlands and the Geer river basin (480 km^2) located at the northern boundary of the Walloon region in Belgium. The latter encompasses the Hesbaye aquifer which supplies drinking water to a total of 600 000 people living in the city of Liège and its suburbs. However, since the 1960s nitrate concentrations in the groundwater have been constantly rising close to the drinking water standard (50 mg/L) with peak values above 175 mg/L in some parts of the upper aquifer. The model approach is capable of coupling flow within three distinct hydrological compartments: the surface, the unsaturated zone and the groundwater body. Utilizing the multi-mesh, multi-process, finite-element simulation code GeoSys/RockFlow each compartment can be discretised independently up to the resolution demanded by the process equations. The computationally sensitive issue of unsaturated flow at large scales is approached by the concept of a (parallelised) regional hydrological soil model. A full annual cycle of meteorological forcings (precipitation, temperature *etc*.) is applied to (physically-based) simulate the water movement across and within hydrological compartments.

Key words groundwater-surface water interface; watershed scale; coupled processes

INTRODUCTION

Large-scale hydrologic models are indispensable research tools for hydrologists to investigate regional hydrological features *e.g.* under the influence of global climate change or land-use changes. Apart from surface water flow, fluid movement in the unsaturated zone is important in hydrological analysis since the vadose zone constitutes the interface between hydrosphere and atmosphere and as such governs the transfer of water and matter between surface and subsurface compartments. Soil moisture patterns influence the recharge distribution to groundwater and on a larger scale wet-dry patterns in soil may also have an effect on convective cells in the atmospheric boundary layer (Patton *et al.* 2005). Moreover, it was demonstrated in a modelling study by Clark *et al.* (2004) that rainfall locations and intensities can be influenced by the presence and size of a wet soil patch down to scales of 10-15 km. Apart from the variation of soil types at large scales the spatio-temporal variation of soil moisture patterns is also dependent on topography, the meteorological forcing (precipitation, air temperature, net radiation) and vegetation cover.

With the recent advances in high-resolution data sampling techniques (*e.g.* remote sensing, direct push methods) and tools for data processing and management at hand, large scale distributed modelling is becoming a more and more a viable option for hydro(geo)logists despite its enormous demand on data and computational resources. In this study, we focus on technical details regarding large scale distributed modelling within the framework of the finite-element (FE) software GeoSys/RockFlow (Kolditz & Bauer, 2004, Wang & Kolditz, 2007), where water flow may be coupled across three distinct hydrological compartments: the (topographic) surface, the unsaturated zone and the groundwater body. Using the multi-mesh, multi-process capability of GeoSys/RockFlow (GS/RF) each individual flow processes may be represented by a FE mesh of its own and coupled via the compartment interfaces.

One focus of this article is the problematic of large scale unsaturated zone water flow simulation. Typically, the solution of the non-linear Richards equation requires a relatively fine vertical FE resolution. However, using a similar resolution for the lateral discretisation of the unsaturated zone would be prohibitive for large scale models. The second focus deals with the generation of a hydrologically consistent FE mesh for overland flow simulation described by the two-dimensional diffusive wave equation. Within two application examples to larger scale watersheds in the Meuse river basin – the Geer river in Belgium and the Beerze and Reusel rivers in the Netherlands – the modelling concepts are demonstrated.

METHODS AND CONCEPTS

Unsaturated zone

For large scale unsaturated zone simulation a so-called regional hydrological soil model (RHSM) was implemented to achieve reasonable mesh sizes and the required vertical discretisation for the solution of the Richards equation. The concept of the RHSM is the use of a local one-dimensional soil column as an effective model segment, that is represented by *e.g.* a mesh of vertical line elements. This line mesh approximates the (essentially vertical) movement of water through the three-dimensional unsaturated zone. Such a one-dimensional approximation is assumed to be valid only for a certain lateral extent, the so-called influence area of the vertical column. The influence area can be given as any polygon which can be chosen in accordance with topography, vegetation, as well as lateral soil profile variability. The origin of the FE meshes for flow computation is the weight centre of the influence area. Its vertical discretisation may then be adjusted to the vertical soil information and numerical needs. An illustration of this concept is given in Figure 1. The top of soil column represents the topographic surface and the bottom is, per definition, the groundwater table. As the groundwater table varies – the line elements will shrink or elongate accordingly. Ultimately, the RHSM is the spatial arrangement of all soil columns connected laterally by their according influence areas. An important assumption of this approach is that flow within soil columns is independent of neighbouring soil columns. This neglects lateral exchange processes and thus is strictly valid only for flat or mildly sloping areas. Principally, lateral flow may be incorporated by the use of prism elements. However, the advantage of a coarser lateral discretisation (using influence areas) is lost, if FE aspect ratios (breadth or width divided by thickness) should be kept reasonable for numerical reasons.

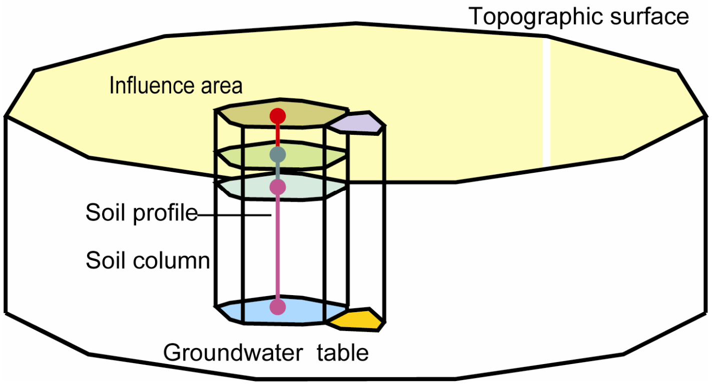

Fig. 1 A schematic illustration of the regional hydrologic soil model concept.

Overland flow

The generation of hydrologic models comprising surface water flow nowadays usually starts with a digital elevation model (DEM). The analysis of flow directions and flow accumulation can be carried out using ArcGIS toolboxes like ArcHydro (ArcHydro_1.2 2007). Within an application of GS/RF such GIS tools are used to extract the watershed outline and the river network, which provide the surface geometry for the three-dimensional watershed model. This vector data then contains closed boundaries (the watershed outline) as well as open boundaries (the river network).

Any FE mesh generator would have to obey both types of boundaries in order to allow consistent river (represented by one-dimensional line elements which are extracted from the overland flow mesh) and overland flow (represented by two-dimensional triangle elements) calculation. For this type of meshing a constraint Delaunay triangulation algorithm was implemented based on Kohara & Taniguchi (2006). As meshing is based on the planar two-dimensional projection of the boundary objects – an elevation mapping of the planar mesh back to onto the three-dimensional DEM may still result in hydrological inconsistencies of the final triangle mesh, *i.e.* small sinks are generated that would cause artificial ponds. This problem seems to occur especially within broader river valleys, where the overall slope is not so clearly defined. A partial remedy was found in using a reconditioned DEM for elevation mapping. The reconditioning was carried out using the AGREE method (implemented in ArcHydro, for algorithmic details see, *e.g.*, Hellweger 1997) which allows to adapt and smooth the DEM within the vicinity of a river dependent on the distance to and type of this river. Further cleaning of weak sinks (defined by a single node) was carried out using a specific GS/RF tool.

APPLICATION EXAMPLES

Beerze-Reusel area

The demonstration of the RHSM is carried out for the Beerze-Reusel area in the Netherlands where a comprehensive regional soil-water characteristic curve database was available (Woesten *et al.*, 2001). The study site is shown on Figure 2 together with an indication of its influence area partition according to the soil characterisation of Woesten *et al.* (2001).

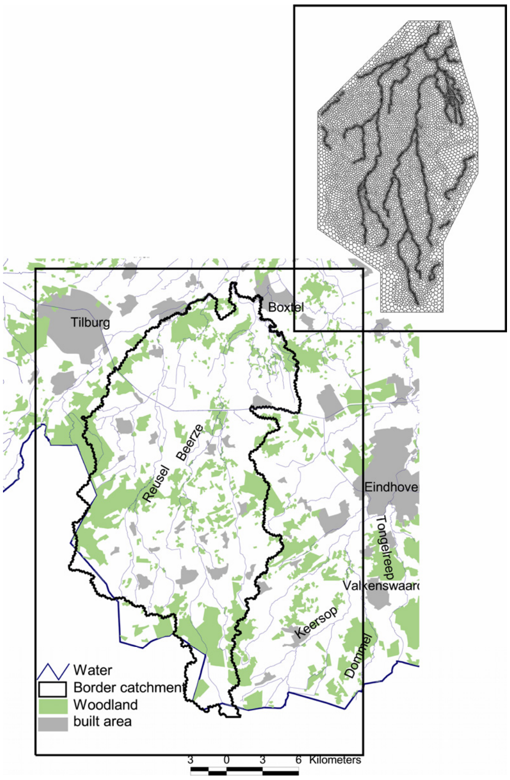

Fig. 2 Outline of the Beerze-Reusel area (the Netherlands) and its according partition into influence areas (upper right corner).

A total number of about 12 000 influence areas are linked to (vertically arranged) one-dimensional Richards problems of 40 line elements per problem on average (average thickness 2 m). This constitutes a massive demand on computational resources. Therefore, the RHSM was parallelised to and run on an 8 CPU node Linux cluster of 64-bit AMD Opteron processors. The parallelisation was carried out using the message passing interface implementation MPICH. Due to the independence property of individual soil columns in the RHSM the total number of individual Richards problems could be divided into groups and each group processed on a cluster node. For a realistic meteorological forcing daily rainfall, temperature and sunshine duration data for the year 2000 was used from surrounding gauging stations De Bilt, Twenthe, Vlissingen, Eindhoven, and Maastricht to calculate infiltration time series (overland flow is neglected here) after removal of (potential) evaporation (calculated by the Makkink method according to van Kraaling & Stol (1997); see Figure 3). The infiltration series were subsequently transferred to the influence areas by day-wise inverse distance interpolation.

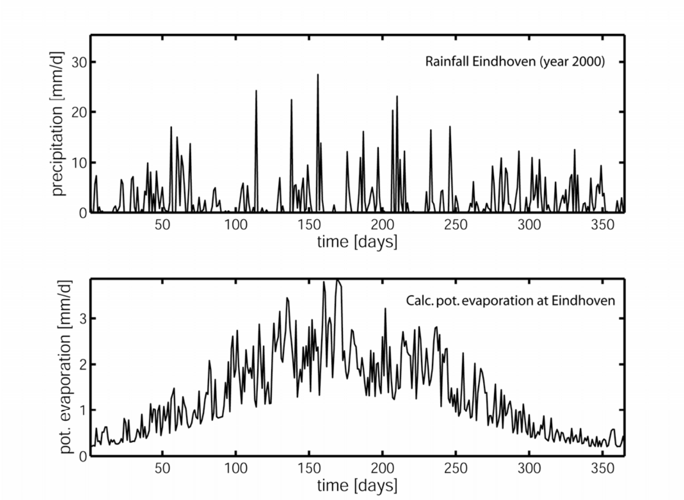

Fig. 3 Measured daily precipitation and calculated evaporation time series of the year 2000 for the gauging station Eindhoven

For the solution of Richards equation a Galerkin finite element method is applied with mass lumping to improve solution convergence and stability. A computed snapshot for day 60 of a regional soil moisture pattern is shown in Figure 4. The vertical and lateral differentiation of soil moisture can be clearly identified. The computational efficiency gain achieved by using the parallel formulation of the RHSM on four nodes was almost 75 % compared to a single node run.

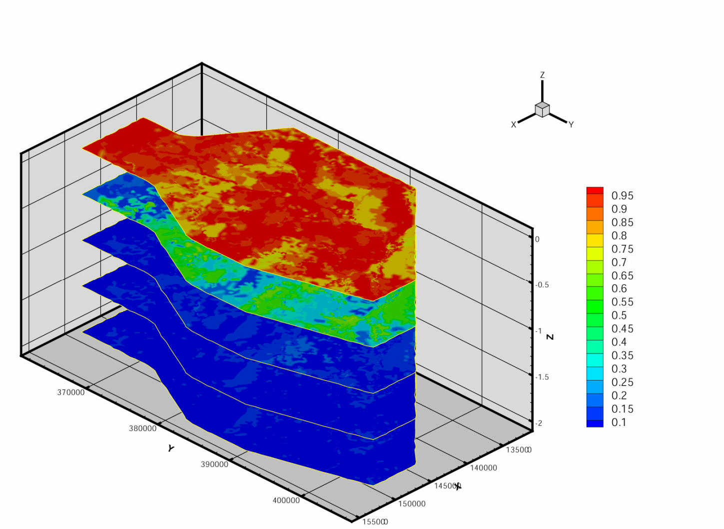

Fig. 4 Snapshot of the calculated soil moisture distribution (color scale is given as saturation fraction) for the Beerze-Reusel area (day 60).

Geer basin

The Geer river basin (480 km^2) is located at the northern boundary of the Walloon region in Belgium. It encompasses the Hesbaye aquifer which supplies drinking water to a total of 600 000 people living in the city of Liège and its suburbs. However, since the 1960s nitrate concentrations in the groundwater have been constantly rising close to the drinking water standard (50 mg/L) with peak values above 175 mg/L in some parts of the upper aquifer which gave rise to detailed research and modelling efforts within the Geer basin (see Brouyère *et al.* 2004, Brouyère 2006). The existing scientific understanding of the hydrosystem and the availablility of a comprehensive database therefore makes the Geer basin a valuable site for large scale distributed hydrological modelling.

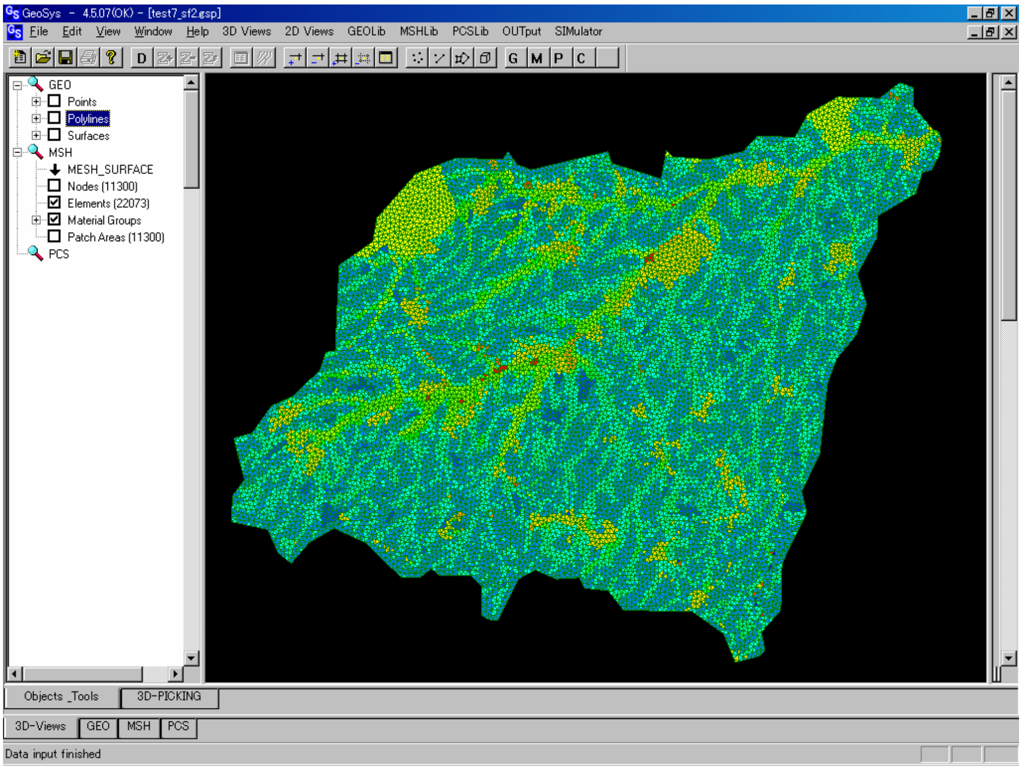

Fig. 5 Outline of western part of Geer basin (Belgium) displayed with Geo-Sys/RockFlow graphical user interface. The triangle mesh is shown together with different material groups assigned based on the available soil type map. The yellow parts depict areas where soil type information is missing.

As described above the available 30 m x 30 m DEM was first processed with ArcGIS to extract the catchment outline and the river network. For this study only the western part of the Geer basin (12 km x 15 km) was considered. The purpose of this small study was to check the meshing procedure outlined above and to test the diffusive wave formulation on the obtained triangle mesh. Figure 5 shows the outline of western part of the Geer basin with the obtained triangle mesh (here set to a mean triangle edge length of 100 m) as well as assigned soil properties based on a soil type map (ArcGIS shp format). Artificial rainfall of 2 mm/m^2 is set as an initial condition and the flow simulation is run for a short term of 25 min (therefore soil infiltration is neglected in this simulation run). For the solution of the diffusive wave equation within GS/RF a control volume finite element method was used.

Figure 6 (upper diagram) shows the water depth shortly after simulation start (2 min). As water drains from the topographic highs to the lows the contour plot of water depths already seems to resemble some features of the topography of the basin. Within the deeper valleys the water depth is also significantly higher. Figure 6 (lower diagram) depicts the drainage from the western part of the basin in contours of water depth after 25 min. Here most of the topographic high regions have dried up and overland flow is chiefly taking place in the deeper valleys. The occasional discontinuities of contours of equal water depth are caused by lateral variations of valley morphology.

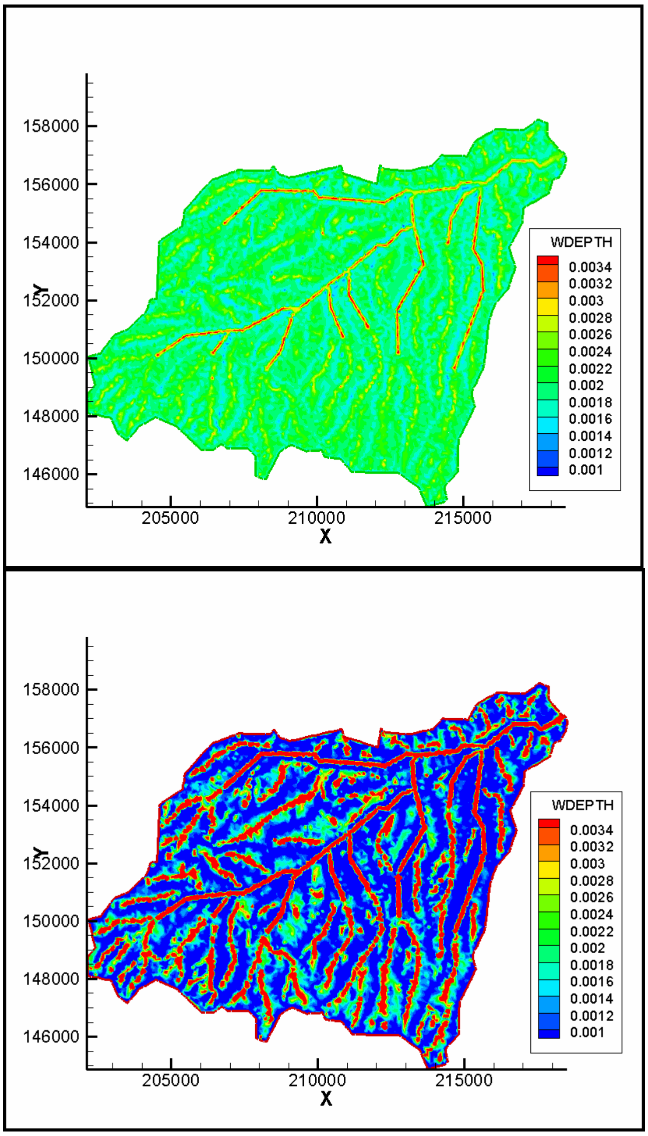

Fig. 6 (upper diagram) water depth (WDEPTH in m) after 2 min of simulation time. (lower diagram) water depth (WDEPTH in m) after 25 min of simulation time.

OUTLOOK AND CONCLUSIONS

Within two application examples the implementation of the regional hydrologic soil model (RHSM) and the procedure for an appropriate triangulation to solve the diffusive wave equation within GeoSys/RockFlow at catchement scale was tested. The results show that the RHSM concept allows the efficient computation of large scale soil moisture patterns while meeting the (vertical) discretisation demand for the accurate solution of the Richards equation. Nevertheless, it is concluded that for calibration runs which may include also the overland and/or the groundwater compartment parallelisation techniques are needed. In that respect the parallel formulation of the RHSM gave promising speed-up results. The Geer example demonstrates that the proposed triangulation and mapping procedures indeed leads to finite element discretisations which are suited for overland flow simulation at catchment scales. Moreover, the preliminary calculated water depth distributions appear reasonable, so that this first test of the solution procedure of the diffusive wave equation on a realistic catchment geometry was successful. A logical next step for the future appears to be the combination of the overland flow mesh with the RHSM and a groundwater compartment for the western part of the Geer basin.

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