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Visual preparation of hydrological models

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Abstract In this paper we demonstrate the functionality of the OpenGeoSys framework for visualisation of simulation-related data. Complex hydrological models are based on a large number of heterogeneous input data sets. In addition to any geo-scientific information such models also include finite element meshes, initial- and boundary conditions, and other data necessary for the simulation of hydrological processes. The visual assessment of this information in 3D space in the process of creating models has proven to be helpful for experts to attain a deeper understanding of the interrelation of data sets and the detection of possible problems or errors. The presented visualisation techniques are applied to a model region at the western Dead Sea escarpment for a simulation of groundwater recharge in an arid region.

Key words visualisation; hydrology; simulation; groundwater flow

INTRODUCTION

Faced with the dangers of climate change, an increasing population and the subsequent expansion of cities there is a growing need for the reliable simulation of hydrological processes to estimate possible risks and to develop appropriate methodologies for a sustainable long-term water resource management for densely populated areas.

To ensure that such complex simulations yield meaningful results, hydrological models are often based on a large number of heterogeneous data sets from a wide range of sources. Examples include raster data, such as digital elevation models (DEM) acquired via satellite, borehole data from industrial drillings, or private wells or sensor data containing time dependent information about precipitation or groundwater levels. Visualisation of these collected hydrological data sets in 3D space is a crucial step for understanding the data and being able to identify relationships between data sets. However, there are a number of potential problems when combining inhomogeneous data sets because of their differences in scale, dimension or format. Many of these issues can be detected via visual inspection of the combined data sets in 3D space or using simple algorithms (Rink *et al.*, 2011a). Adjustments need to be performed manually in most cases, depending on properties of the data and the subsequent simulation. Once all the data necessary for simulating a hydrological process have been assembled, the information regarding the actual simulation has to be compiled. This includes the generation of a finite element mesh, as well as definition of initial conditions, boundary conditions, material properties, etc. For complex simulations, this second set of data can also be quite comprehensive and an adequate visualisation of this information has to be considered. While a colour-coded display of different stratigraphic layers or material properties in subsurface meshes is quite common and can be found anywhere from geologic modelling software such as GOCAD (http://www.pdgm.com) to simulation software like GMS (http://www.aquaveo.com/gms) or Eclipse (http://www.slb.com), examples for the visualisation of process conditions are rare. To our knowledge only a small number of commercial tools include visualisation techniques of such data. For hydrological simulations, the most well-known example is FEFLOW (2010) which highlights and inflates boundary conditions and displays time variant information in a diagram.

VISUALISATION OF SIMULATION-RELATED DATA

We employ the *OpenGeoSys Data Explorer* framework (Wang *et al.*, 2009; Rink *et al.*, 2011b) for the preparation of hydrological models, the simulation of processes, and the visualisation of data

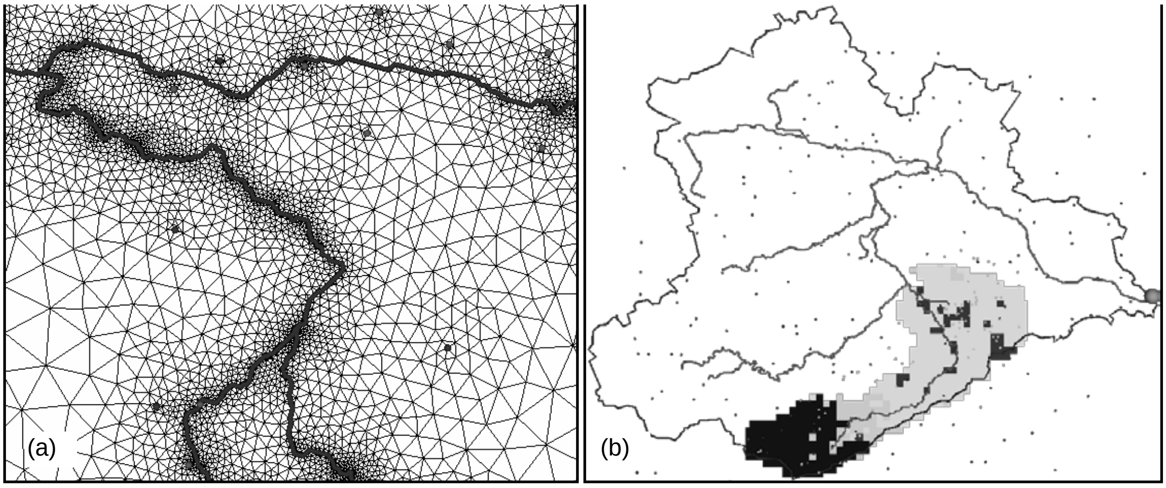

Fig. 1 (a) Integration of additional information into a mesh. (b) Examples of source terms applied to points (e.g. wells, river run-off), polylines (e.g. rivers, faults) or surfaces (e.g. precipitation maps).

as well as simulation results. The framework is platform-independent and based on the open source libraries Qt (http://qt.nokia.com) for implementation of the user interface and VTK (http://vtk.org) for the visualisation of graphical objects. It allows the import of hydrological and simulation related data sets in various formats (Rink, 2011b) and offers a set of general visualisation techniques that can be applied to any data set:

– The visualisation of objects can be super-elevated which is especially useful for hydrological models as the extent in x- and y-direction is often much larger than in z-direction (e.g. in the case study presented in the next section, the extent in x-direction is 130 km while the extent in z-direction is less than 6 km).
– User-defined colour-lookup-tables can be defined for any data set or parameter to ensure an optimum recognition value for different kinds of data and its properties. A typical example is visualisation of stratigraphic information from boreholes using standardised geologic map colours.
– Each data set has an independent opacity value such that the potential problem of one data set occluding another can be avoided by using a semi-transparent visualisation.

For the preparation of hydrological processes, such as groundwater recharge or overland flow, finite element meshes based on geological and hydrological data can be designed using the framework. For instance, to generate a surface mesh of the model region in 3D, only a DEM and the boundary of the region of interest (ROI) are needed. Adding information based on boreholes, fault lines, river networks, etc. will generally result in a more useful mesh and therefore should also be integrated if it is relevant for the subsequent simulation (Fig. 1(a)). For instance, the generation of a meaningful subsurface discretisation is often based on an interpolation of the stratigraphies of boreholes via kriging (Stein, 1999). Based on this information, each mesh element is assigned an ID that links to properties of the material represented by that element (such as porosity, permeability, etc.) (Fig. 2(a)).

The resulting mesh has to fulfil certain conditions due to the numerical properties of the system of partial differential equations that is used for the simulation of the selected process. For instance, the simulation of mass transport processes explicitly requires a fine mesh resolution in vertical direction to ensure a stable solution (Courant, 1928). On the other hand, processes such as groundwater recharge consist mainly of layered flows, meaning that large differences between horizontal and vertical dimensions of mesh elements might have no effect on a correct result. In Rink *et al.* (2011a) we discuss a number of ways to calculate and visualise mesh element quality within our framework, based on element properties such as volume, angles or the ratio of edge lengths (Fig. 2(b)). This analysis allows for the detection of deformed triangles or elements with

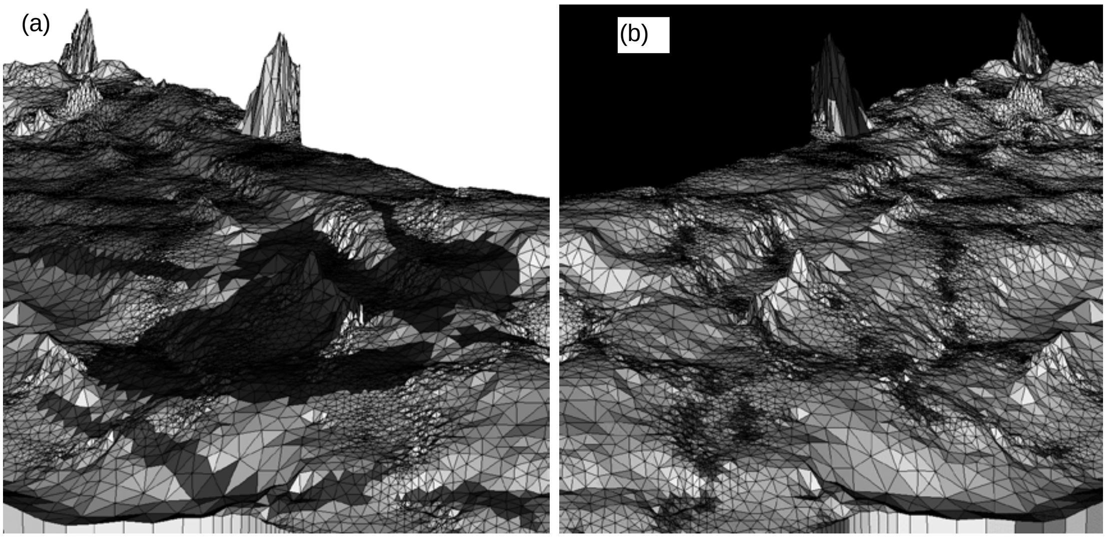

Fig. 2 Visualisation of a finite element mesh with shading schemes based on (a) material groups and (b) mesh element quality (ranging from white (good) to black (bad)).

zero volume which might result in numerical problems during the subsequent simulation. Other measurements to validate the quality of mesh elements have been presented in Knupp (2000) or Shewchuk (2002). Additional functionality for an assessment of the finite element mesh includes the application of thresholds to any property of a mesh element. This gives the user the option to visualise only a subset of the materials within the model domain, to select elements with an especially good (or bad) element quality or – assuming that a simulation has been performed on a mesh – to select any subset of calculated properties, such as setting the focus to regions with a groundwater recharge above or below a given level.

After creating an acceptable mesh for simulation of the selected process, a number of initial conditions, boundary conditions and source/sink terms have to be assigned. For hydrological models source terms are usually assigned to locations representing river runoffs, extraction wells, regions with known precipitation, etc. (Fig. 1(b)). For this reason it is useful to include this information into the mesh, as described above. In our framework, all FEM-related conditions can be verified in a tabular tree view which offers information about the process and the geometrical object the condition is assigned to as well as its type (e.g. Dirichlet or Neumann) and actual

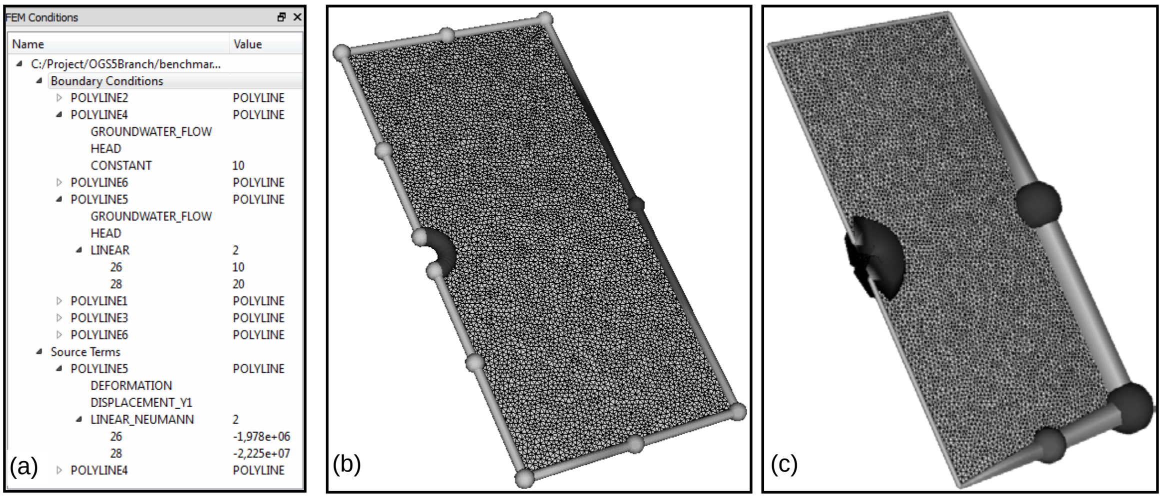

Fig. 3 Visualisation of boundary conditions (a) in tabular tree structure and (b) in 3D space with shading based on numerical value and (c) with radius based on numerical value.

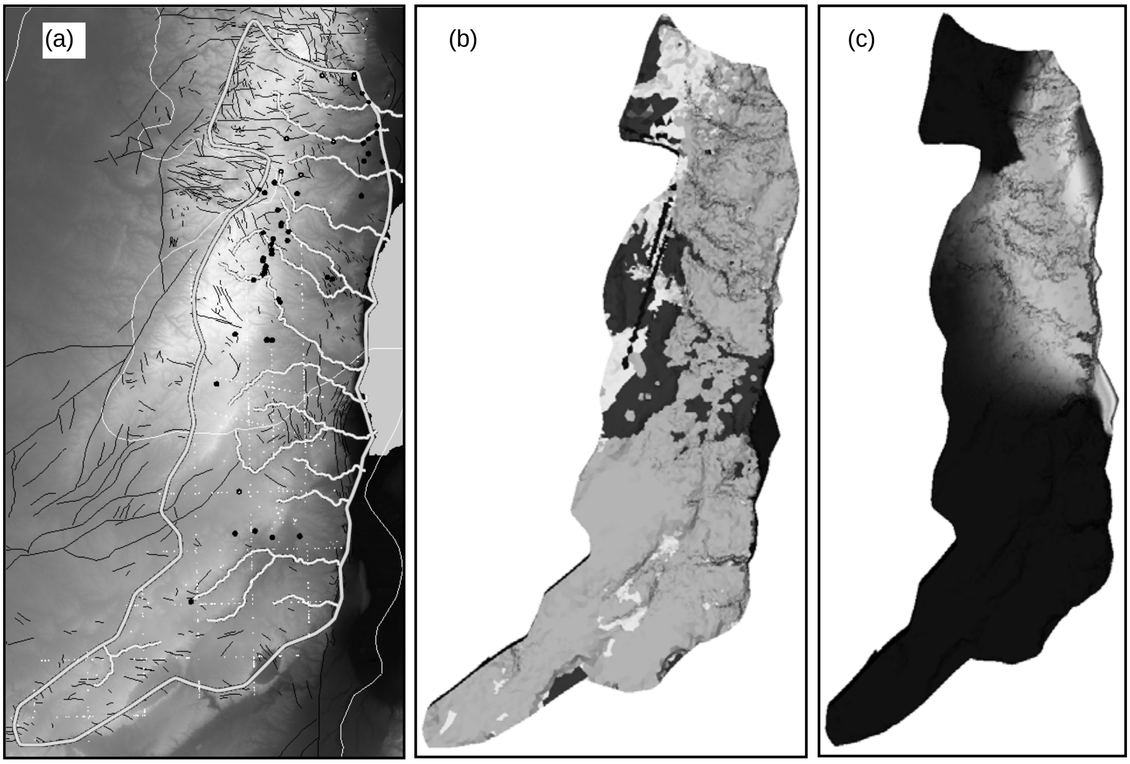

Fig. 4 Visualisation of data from Dead Sea case study: (a) integrated input data, (b) material groups in finite element mesh, (c) simulation result

numerical values (Fig. 3(a)). For visualisation in 3D space these conditions are represented by geometrical objects (i.e. points, polylines or triangulated surfaces) and their appearance is independent of any other information. Each condition can be represented by a user-assigned colour, such that, for instance, all boundary conditions related to groundwater flow are displayed in red while boundary conditions related to overland flow are displayed in blue. As an alternative, the colour of a condition can represent its actual numerical value (Fig. 3(b)), thus allowing an instant assessment of the potential impact of a certain condition. Furthermore, it is possible to inflate geometrical objects representing process conditions for better visibility. To be specific, points are displayed as spheres or lines are displayed as tubes, as seen in the examples depicted in Fig. 3. This functionality is often necessary as boundary conditions or source terms are often applied to isolated points within a large model region (such as observation wells) and are thus difficult to see given all the other information. As an example, note the large sphere on the right boundary of Fig. 1(b) illustrating river runoff. It is also possible to use a combination of both techniques, e.g. scaling the radius of the visual representation of a condition by its actual numerical value while assigning a colour based on process type or whether the object represents a boundary condition, an initial condition or a source term (see Fig. 3(c)).

The functionality proposed above supports the preparation of hydrological models by allowing a visual assessment of the data to avoid potential problems concerning the domain discretisation or the assignment of process conditions. Once the simulation is finished, results can be visualised on the finite element mesh. To allow for a better understanding of the process inside the model domain, it is also possible to display contour-lines or -surfaces instead of the complete mesh. A combined visualisation of input data and simulation result is helpful for validating the plausibility of the result. Finally, as mentioned before, subsets of the result can be selected by thresholding, thus allowing the user to detect and focus on especially interesting parts of the result.

CASE STUDY

To demonstrate the application of the proposed visualisation methods we apply them to the data from a model region located in Israel and Palestine. The region has a size of 3800 km^2 and is characterised by arid to semi-arid conditions where groundwater is the only reliable source of fresh water. Due to high demands to the groundwater system water shortage is a common problem in that area (Guttman, 2000; Hötzl *et al.*, 2009). The corresponding study is concerned with the modelling of surface and subsurface inflow of water into the Dead Sea along the escarpment on its western shore. For more details on the study, the interested reader is referred to Gräbe *et al* (2011).

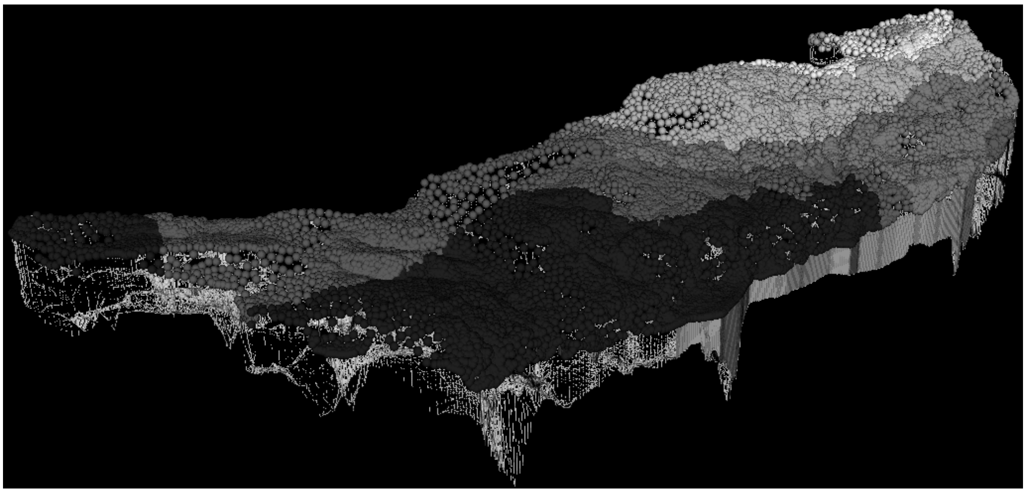

Fig. 5 Visualisation of boundary conditions and source terms: The dots symbolise precipitation for each surface mesh node. The large dark surface in front of the mesh marks the groundwater inflow into the Dead Sea along the western escarpment.

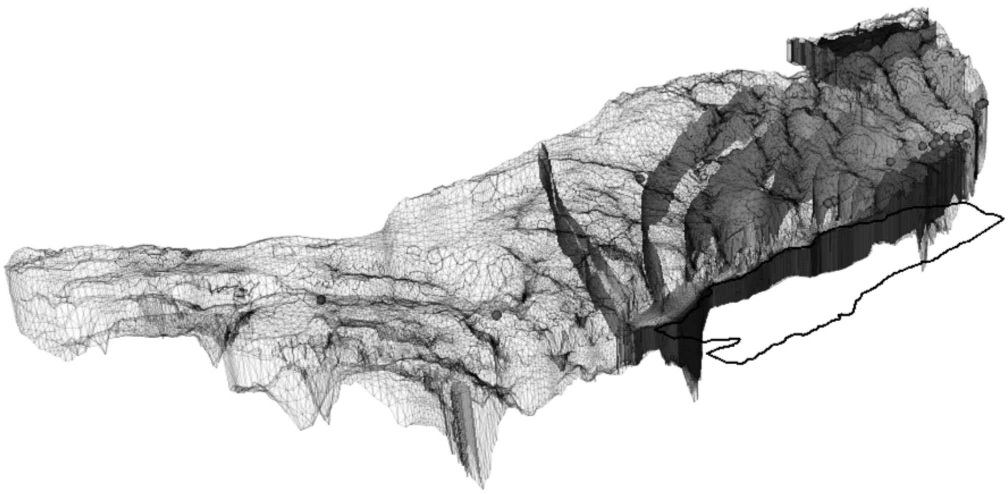

Fig. 6 Combined visualisation of input data, finite element mesh and simulation results. The dark line on the right hand side marks the boundary of the Dead Sea, the dots symbolise wells in the area. Simulation results are depicted as contour plot.

The discretisation of the model domain is based on a large set of input data depicted in Fig. 4(a). It takes into account surface information derived from a DEM of the region with a resolution of 30 m as well as the course of a number of wadis (i.e. riverbeds, thick white lines) and wells (black dots) located in that area. The subsurface area has been interpolated based on information from 579 borehole stratigraphies (white dots) and also includes information of faults (thin black lines) having a notable impact on the groundwater flow. For geographic reference the figure also includes the Dead Sea area (light grey on the right hand side) und the border between Israel and the West Bank (thin white line). The resulting finite element mesh consists of 114 327 nodes and 184 481 tetrahedra- and prism-elements. These elements have been assigned properties of over 40 different materials (see Fig. 4(b)). For configuration of the groundwater flow simulation, measurements of the groundwater head at 15 observation wells have been employed as boundary conditions. The source terms of the system are based on precipitation in the area and groundwater runoff into the Dead Sea (see Fig. 5 for a visualisation using the proposed techniques).

An iteration of the resulting groundwater flow simulation is depicted in Fig. 4(c) (mapped on the finite element mesh) and in Fig. 6 (visualised as a contour plot). Figure 6 also contains the location of wells and the Dead Sea boundary for reference. It can be seen that the gradient of the groundwater head is much larger in the northern part of the model area (right hand side of Fig. 6) where a large number of wells are located.

CONCLUSIONS AND FUTURE WORK

We presented a number of visualisation techniques for simulation-related information of hydrological models. A combined visualisation of hydrological data, process-related information and/or simulation results allows for a better understanding of the data, an assessment of potential problems and supports experts in validating the simulation results. We applied the proposed techniques for a case study concerned with groundwater flow in a semi-arid region to demonstrate their application for a non-trivial case.

As this is a work in progress, we are aware that there are quite a number of techniques and issues that are at this point not available in our framework but would be very useful to include. The visualisation of material properties is currently limited to a few special cases and needs to be expanded to work for arbitrary combinations of properties. The calculation of mesh quality measures should be dependent on the type of simulation the mesh will be used for, this includes the addition of adequate quality measures for the associated process types. Finally, an adequate visualisation of time-dependent boundary conditions is mandatory for applications of the proposed visualisation techniques for complex case studies.

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