MODELLING GROUNDWATER FLOW ON THE REGIONAL SCALE IN THE UPPER DANUBE CATCHMENT (GERMANY)

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Abstract. A groundwater flow model for the Upper Danube catchment (A=77,000km^2 at gauge Passau, Germany) has been developed within the framework of the interdisciplinary research project “GLOWA-Danube”. The model is part of the Decision Support System “DANUBIA”, which is comprised of 15 individual yet fully coupled models. Modelling of groundwater flow, using coupled deterministic and hydrological approaches for large catchment areas, brings about several challenges which are unknown or of minor importance on smaller scales. The three main challenges are: Firstly, how to appropriately represent a complex aquifer geometry on a necessarily relatively coarse grid? Secondly, how to include large sub-domains within the model area, which can not be modelled as a layered aquifer system (in the present case represented by the mountainous areas of the Alps)? Thirdly, how to deal with the existence of sub-domains that are characterized by very deep regional groundwater tables? Solutions to these questions and first results are presented.

Keywords: Regional Groundwater Flow Modelling, Hydrogeological Conceptual Model, Danube, Regionalisation

PROJECT BACKGROUND

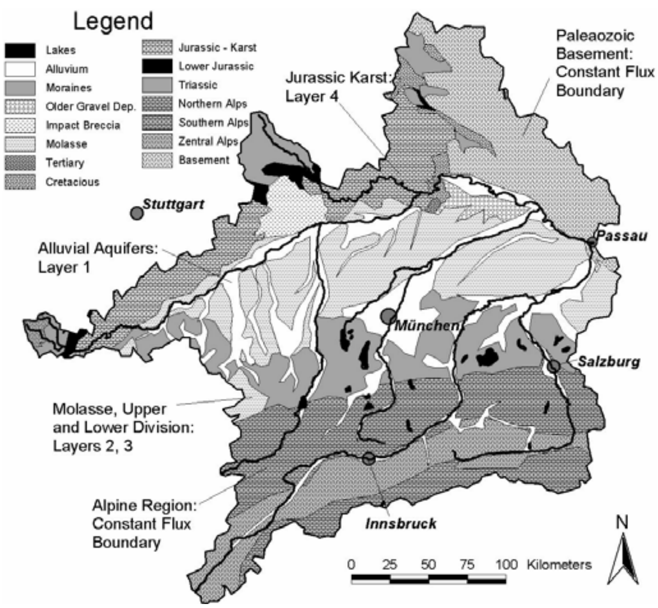
This paper describes the most crucial aspects of the development of a complex regional (mesoscale) groundwater flow model of the Upper Danube Catchment. The model has been developed within the framework of the interdisciplinary research project “GLOWA-Danube” and is part of the Decision Support System (DSS) “DANUBIA”, which is comprised of 15 fully coupled models. The fact that the groundwater flow model is part of a coupled system (partner models include, among others, the “Rivernetwork Model” [rivers / in- and exfiltration], the “Soil Model” [unsaturated zone / recharge] and the “Watersupply Model” [calculates the extraction from wells]) has some important implications that have to be pointed out very clearly. Firstly, the research partners have agreed on a common spatial model environment. All processes are modelled and all parameters are exchanged in a raster environment on a 1*1 km grid. A 1*1 km grid cell in the strictly object oriented environment of DANUBIA is called a Proxel and has a number of functionalities. However, a fixed grid causes problems in the attempt to represent small but significant hydrogeological features and thin near surface aquifers. Secondly, the coupled models expect the groundwater model to be consistent throughout the catchment area. Therefore, it is not possible to simply exclude complex areas, such as the high mountains of the Alps, from the model domain and to represent them as boundary conditions. The project GLOWA Danube and the DSS DANUBIA are described in more detail in another contribution to this conference (Barthel, Braun & Mauser).

THE DANUBIA GROUNDWATER COMPONENT

Recently distributed hydrological models allow for the detailed description of the hydrological and energy cycles in large catchment areas and play an important role in modern integrative water resources management. The groundwater component is a decisive part of such a hydrological model and hence must be accurately modelled. This may be achieved with a deterministic numerical groundwater flow model. However, such complex models have the drawback that their calculation times are very high in comparison to the calculation time of other components of the hydrological model. One obvious method to reduce the calculation time is to restrict the underlying conceptual model to the main geological layers and to apply a finite difference approach on a coarse grid. While this leads to a faster simulation and calibration of the groundwater model, it may also result in serious physical and numerical problems.

The conceptual hydrogeological model

The construction of a conceptual hydrogeological model for such an enormous heterogeneous area (Figure 1) is a task which requires not only the collection of extremely large quantities of data, but also the use of advanced data managing and evaluation tools. The conceptual model consists of four layers, comprising the strata “Jurassic Karst”, “Younger Tertiary”, “Older Tertiary” and “Quaternary” (Figure 2). Only aquifers with basin-wide occurrence are considered due to insufficient data availability, the model grid resolution ($1km^2$), and requirements of the MODFLOW approach. The Quaternary layer is mainly defined by small and thin local structures of high permeability (valley aquifers, alluvial gravel plains). This uppermost layer is most important for short and medium term groundwater flow. Its importance in DANUBIA is clear; it represents the interface to many of the other models. Unfortunately, the complicated geometry of the Quaternary layer makes it the most difficult to model. Importance and complicacy of the layer brought it into the centre of research activities (see below).



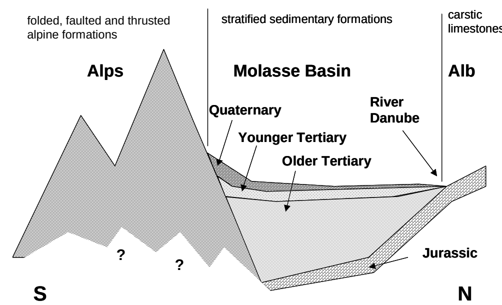


***Figure 2**: Schematic geological cross section of the upper Danube basin showing the four model layers.*

***Figure 1** (left): Schematic geological map of the upper Danube basin*

The numerical groundwater flow model

The main aim of the groundwater model within DANUBIA is to assess and forecast quantity and quality of the groundwater resources under conditions of global change together with the other physically based models. Commonly conceptual hydrologic approaches are used to describe the water balance of groundwater systems in large areas. However, since the distribution and change of hydraulic heads with time is an essential parameter in a coupled system like DANUBIA, a model that is capable of considering the horizontal components of groundwater flow is required. That is to say, the concept of DANUBIA requires that the groundwater model responds to certain processes modelled by other model components in a certain way. For example, extraction from wells should lead to a measurable local and regional drawdown in order to be able to asses environmental impact. As a second example, nitrogen applied by farmers, and later on, leaching through the unsaturated zone, should be traceable from or to a certain drinking water well or a certain river reach. These requirements make the use of a three dimensional transient groundwater flow model inevitable. In accordance with the size of the model area and the raster-based DANUBIA approach, a finite-difference model approach (MODFLOW; McDonald & Harbaugh, 1988) was chosen. The choice of MODFLOW is also justified by the constraint to use open source models and by the proven robustness and relative simplicity of the code. Access to the source code and relative simplicity are desirable because of the need to include the code into the much larger framework of the coupled, network based DANUBIA system. A more detailed discussion of the parameterization of the model would require a detailed description of regional and local particularities and is not feasible here. Problems of more general significance are pointed out in the following chapter.

Crucial aspects of groundwater flow modelling on a very large scale

Three major problems have proven to be decisive in the attempt to successfully model the groundwater flow dynamics of a coarse regional groundwater model with complex geological conditions:

a) The appropriate representation of the complex aquifer geometry on a coarse grid. After the identification of the regional aquifer systems and the creation of a hydrogeological conceptual model, it is important to implement this concept into the groundwater model such that a stable numerical solution of the model is attainable. The main problem is to achieve a connected aquifer system which is able to receive the groundwater recharge in the mountainous areas (Alps to the South, Figures 1, 2) and which yields a reasonable base flow at existing gauging stations in the forelands. Due to the discrepancy between the finite difference cell size and the extent of the narrow, highly permeable aquifers, additional highly permeable cells have to be “added” in order to achieve a closed solution for groundwater flow using a finite difference scheme. In addition, it has to be ensured, that each cell of this “virtual” aquifer has at least one neighbouring cell (in the direction of groundwater flow) with a lower base to guarantee the conductivity of the aquifer. The concept just briefly described was used to implement an algorithm that allows the detection of cell whose permeability needs to be adjusted and to add cells to the modelled aquifer layer. The algorithm was applied to the catchment of the Upper Danube. The modelling results of a finite difference groundwater model in this area using an adjusted aquifer geometry, are very promising. Measured groundwater levels in the gravel aquifer can be modelled with an accuracy of less than two meters (Figure 3). Without a proper investigation of the regional aquifer system and the application of the presented algorithm for the discretisation of such a system, the modelling of regional groundwater flow on a coarse finite difference grid would not be possible at all.

b) In the Alps and a crystalline region in the northeast of the basin (Figure 1) only small, disconnected saturated zones exist. Groundwater flow is restricted to fracture zones or karstic systems, which under the given constraints, and because of missing data, cannot be included in a regional model. The alpine section of the model area is a subject of particular concern. On the one hand, the alpine regions, covering approximately 30% of the catchment area and contributing about 40% of the total precipitation, evidently play a major role in the water cycle of the region. On the other hand, it is not possible to treat the extremely faulted, folded, and thrusted stratigraphic units of the Alps as ordinary quasi-horizontal layers as they are usually described in the MODFLOW concept. Different alternative modelling approaches are available (explicit description of fracture and matrix flow, double-porosity model, etc.), however, their implementation poses difficulties, either because the theoretical foundations of the method are still in development, or simply because of the lack of data needed to parameterise the model. As one cannot extrapolate point data to obtain area information (as it is done for porous media), no direct (measured or estimated from measurements) quantitative assessment of the effective parameters characterising groundwater fluxes through rock masses can be performed. In order to overcome the problems described above, a combined deterministic-conceptual approach was developed and implemented. In this approach, the finite-difference Darcy law based model was extended to its maximum validity domain, namely to the alluvial aquifers draining the water from the mountains into the foreland. For the rest of the area, separated into hydrological sub-catchments built on the base of the digital elevation model, conceptual hydrological models were conceived. Linear reservoirs and linear reservoir cascades have the advantage of being stable, easy to implement tools to describe and quantify water flow when little to no direct information is available. Further more, if the parameterisation, the calibration, and the validation of these models are done in a consistent way, the reservoirs’ constants and the number of reservoirs used in the cascade (which must not be an integer, if the incomplete gamma function is used as a weighting function) can be seen as effective parameters of the attenuation and translation of physical processes occurring in the rock mass. For the calibration and validation process, the computed and the measured discharge time series at the end of every sub-catchment was compared. An extra subtlety was used by calibrating the results of the single parts of the model (outflow of the alluvial aquifer model and of the reservoir models) individually after performing a multiple river discharge hydrograph separation operation, using a digital filter algorithm. The digital filter frequency and the number of filter passes were taken into consideration as calibration parameters.

c) In a coupled regional model, the groundwater recharge, commonly defined as the amount of water percolating through the plant-influenced soil zone, has to be determined considering the processes in the deep unsaturated zone, where horizontal unsaturated/saturated flow can predominate. In sub-domains that are characterized by very deep regional groundwater tables, or deep, confined aquifers, perched aquifers, which cannot be modelled in a regional model, predominate in the uppermost part of the subsurface (0-200m). On the regional scale, perched aquifers have to be treated as part of the unsaturated zone. Horizontal flow leads to discharge of percolating water in springs and small tributaries. It has proven to be extremely difficult to determine the actual recharge to the deep groundwater system, in particular because data to describe this deep, partly saturated zone does not exist. The approach to tackle this problem is to regionalize the factors that determine the amount of horizontal discharge and the deep percolation rates of the deep, unsaturated zone, and use them to parameterize the corresponding transfer functions. However, no satisfactory solution to this problem is available yet, and the authors are convinced that a considerable amount of basic research on all scales is still required.

Results

The current working version of the groundwater model has been successfully run and tested within the DANUBIA environment after careful adaptation of the model geometry, parameter upscaling and calibration for both steady state and transient conditions. Figure 3 shows the resulting piezometric heads of the groundwater component in comparison with the mean values of 1371 measured time series of groundwater levels. The correlation is very good, especially for the data of the quaternary aquifers. Bad results are obtained in the karstic aquifer due to the difficult parameterisation of this aquifer. New approaches (for example, the implementation of a double porosity in MODFLOW) could help to improve the results. Figure 3 also confirms the problem mentioned in c): The groundwater component in DANUBIA models a regional tertiary groundwater level. Local perched aquifers can not be considered by the model, although the groundwater levels in these perched aquifers are often the measured levels in Figure 3. Therefore, the modelled results in the tertiary aquifer are often lower than the measured ones. These results are preliminary and need to be discussed and the approaches to be improved. However, they prove that even with such a coarse grid, a meaningful representation of the piezometric heads is possible.

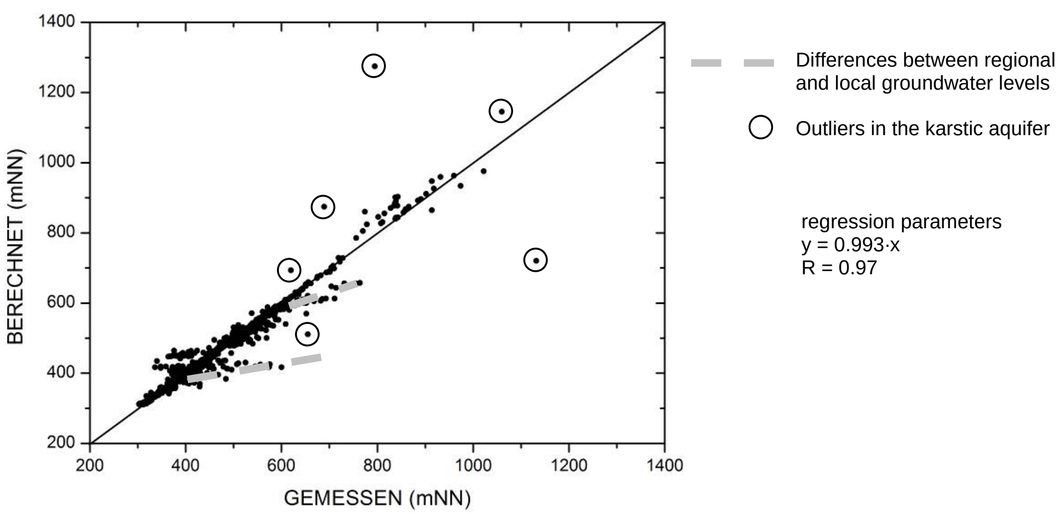


***Figure 3**: Measured (x-axis) against computed groundwater levels (y-axis), both values are in m.a.s.l. (mNN)*

References

McDonald M G and Harbaugh A W 1988. A modular three-dimensional finite-difference ground-water flow model: *U.S. Geological Survey Techniques of Water-Resources Investigations, book 6*, chap. A1, Washington, U.S.A.