How to model groundwater flow on the regional scale in hydrogeologically complex regions?

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Abstract: This contribution deals with the question of whether deterministic, three-dimensional numerical groundwater flow models are the appropriate and only means to meaningfully represent groundwater resources on the river basin scale in the context of Integrated Water Resources Management. The discussion is based on two case studies from the Upper Danube catchment (77 000 km^2) and the Neckar catchment (14 000 km^2) where groundwater flow models (MODFLOW) were developed and integrated into river basin management decision support systems. The results of the analysis are ambiguous: From a theoretical point of view, it is obvious that only numerical 3D groundwater flow models can provide the results that are required to manage groundwater resources in hydrogeologically complex regions (more than one aquifer; dipping, faulted, non-uniform formations). On the other hand, from a practical viewpoint, it proves to be difficult to develop models which provide results with the required accuracy and reliability. It is crucial to define the modelling objectives and concepts very carefully in order to find the correct balance between decision maker's requirements, data availability, hydrogeological characteristics and complexity of the region and finally usability and performance of the numerical tools.

Keywords: Regional Scale, Groundwater Flow Model, MODFLOW, Neckar, Danube

1. Introduction

Many water management tasks, such as the evaluation of the impact of climate change and the establishment of river basin management plans - as requested by the European Water Framework Directive - require a regional assessment of the state and future of water resources. Models are important tools that help to understand systems, to predict changes and to support decisions with far-ranging implications. Since groundwater is a major drinking water source in many parts of the world, the groundwater system and its accurate representation play a major role. Physically-based, deterministic, numerical 3D groundwater flow models are the only means to calculate spatially distributed hydraulic heads in different aquifers and by that way to describe horizontal as well as vertical flow, to calculate flow direction and velocity and to quantitatively simulate groundwater discharge to surface waters. A disadvantage of these models is the amount of variables and parameters they need and the fact that these parameters are often difficult and expensive to determine. Therefore, to set up a groundwater flow model that can actually provide the aforementioned results in a meaningful and realistic way is not a simple task. Typical groundwater models are used on much smaller scales, or only for homogeneous aquifers. In river basin management, conceptual hydrological models are usually used to represent the groundwater system in a very simple way. This seems to be one reason, why numerical 3D groundwater models for hydrogeologically complex areas (i.e. multiple aquifers, complex relief etc.) of more than 10 000 km^2 are relatively scarce. On the other hand, the Global Change research, which requires means to bridge the gap between global models and local scales, has triggered the need for developing regional scale models. The issues discussed in this paper are the following:

1) Physically-based groundwater models applied on a regional (river basin) scale necessarily have to have a relatively coarse discretisation in order to achieve feasible computational times and manageable storage demands. Therefore the natural conditions in hydrogeologically and geomorphologically complex regions can not always be represented in a meaningful way.

2) In most cases, data required for model parameterization, definition of initial and boundary conditions and finally model calibration is not available in sufficient amounts in all parts of a river basin.
3) It follows from 1) and 2) that regional model results cannot be downscaled to solve local problems. However, many groundwater related problems *are* of a quite *local* nature. Therefore management and modelling tasks need to be included in the considerations of which model to use.

The previous list of issues shows that the question remains open as to whether regional numerical groundwater flow models of high complexity are really an appropriate means to solve regional groundwater related management problems. In the present article these questions are discussed using the example of three regional groundwater flow models (Neckar catchment, Germany, 14 000 km^2, Southern Ouémé Basin, Benin, 11 000 km^2, and Upper Danube catchment, Germany, 77 000 km^2) which were developed within the framework of the integrated management projects RIVERTWIN (www.rivertwin.org, Gaiser et al., 2007) and GLOWA-Danube (www.glowa.org; www.glowa-danube.de, Mauser and Strasser, 2005). The groundwater flow models are integrated into coupled management models. All three models were evaluated with respect to the question of whether the chosen modelling approaches (multi-layered finite difference numerical flow modelling, steady state and transient - MODFLOW) are appropriate in view of the existing management problems in the catchments, the data availability and the hydro***geo***logical and hydrological conditions in the basins.

2.Case Studies

2.1. Project backgrounds and study areas

Within GLOWA-Danube a large scale three-dimensional numerical groundwater flow model has been developed for the Upper Danube catchment (Barthel et al., 2005; Barthel et al., 2007a). The model runs within the DANUBIA framework coupled to 16 other models and produces reasonable results in most parts of the model domain (DANUBIA: Barth et al., 2004, Mauser and Strasser, 2005). Models are connected to each other via customized interfaces that facilitate network-based parallel calculations, i.e. models exchange data at runtime.

Within RIVERTWIN two large scale groundwater flow models were developed for the Neckar Catchment, Germany and the southern part of the Ouémé catchment (Barthel et al., 2007b). The models are part of the river basin management tool MOSDEW (MOSDEW: Gaiser et al., 2007). MOSDEW represents a loose coupling scheme. The individual models are coupled via data sets that are calculated after a prior model adjustment and calibration. The integrated framework is a GIS-interface that draws upon result data from a huge results data base. In order to run scenario simulations, data sets for reference years are combined in the desired number and sequence.

The discussion in the present article is mainly based on the two modelling case studies in Germany (Neckar, Upper Danube). However, the conclusions drawn stem also from the Ouémé basin (Benin) modelling exercise (for more details see Barthel et al., 2007b) even if this case study and its results are not explicitly described in this paper. Fig. 1 shows the location of the two basins in Germany.

The dominating geomorphologic features in the Danube Basin are the Alps to the south (Fig. 2). They make up about 30 % of the region but receive more than 50 % of the precipitation. The complex geomorphology makes it especially difficult to model groundwater flow in this part. On first sight, the geomorphology of the Neckar Basin seems to be comparably simple (see Fig. 3) since the relief gradients are quite small. The Neckar Catchment is dominated by deep river valleys that cut into a rolling to slightly mountainous landscape. The typical alluvial planes and valleys of the Danube area are missing. Therefore the interaction of groundwater and rivers is very difficult to model.

Both basins are very complex with respect to geology and hydrogeology. In the upper Danube Basin, the Alps, crystalline and carstic areas area extremely heterogeneous and the hydrogeological situation is dominated by small scale local features. On the other hand, in the Danube Catchment we find a wide "basin type" area (Molasse Basin), which is dominated by unconsolidated, porous quite homogeneous rocks. In this basin part it is possible to model groundwater flow very successfully. In the Neckar Basin, the geological situation is dominated by quasi-horizontal Mesozoic formations. Limestones, sandstones and siltstones form fractured or carstic areas. The hydrogeological sequence is highly differentiated vertically resulting in a high number of individual aquifers separated by rocks of low permeability.

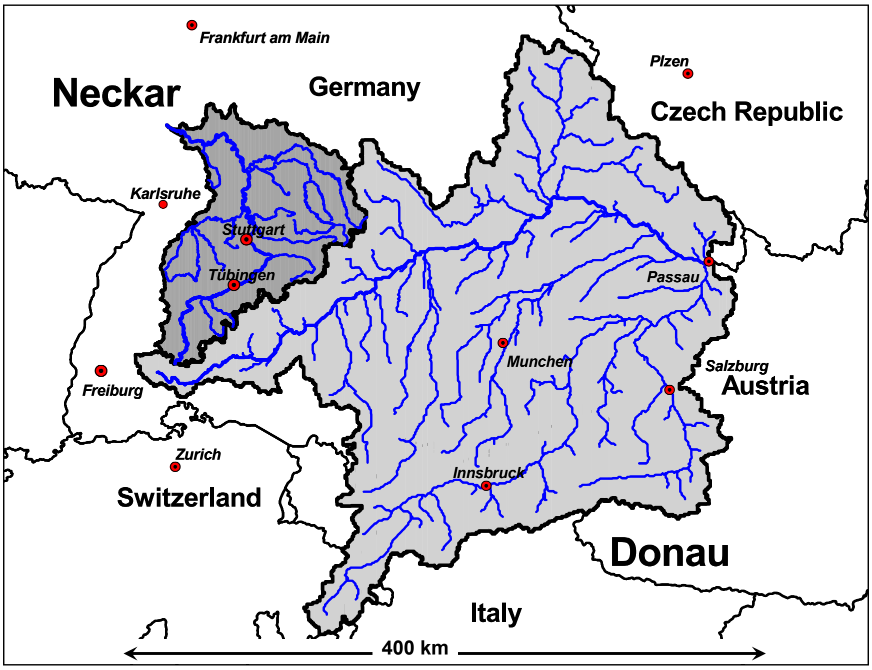

Fig. 1: Location of the Neckar catchment and the Upper Danube (‚Donau') catchment

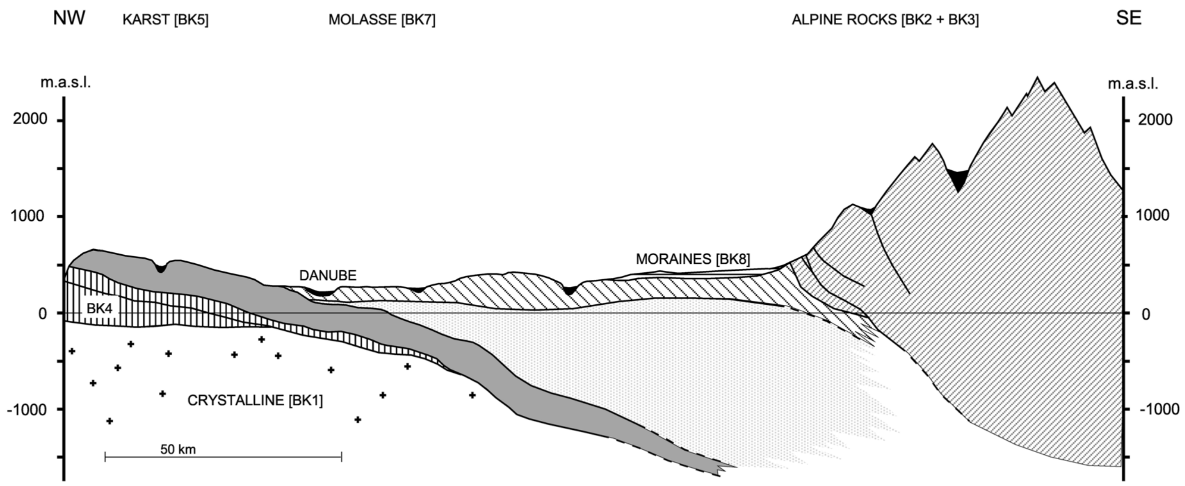

Fig. 2: Geological-hydrogeological cross section of the Upper Danube catchment.

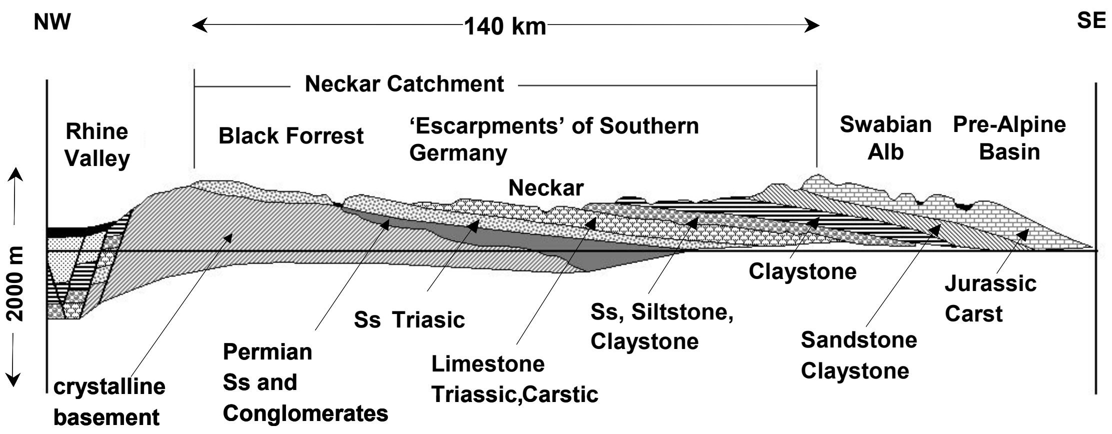

Fig. 3: Geology of the Neckar basin – cross section

2.2. Conceptual and numerical groundwater flow models

From the previous section it becomes evident, that the Neckar and the Upper Danube Basin, though adjacent (Fig. 1), are different with respect to geomorphology and hydrogeology. Nevertheless, the same modelling approach (Finite Difference, MODFLOW, McDonald and Harbaugh, 1988) is used for groundwater flow modelling. The main characteristics of the models are shown in Table 1:

Table 1: Main characteristics of the regional numerical groundwater flow models (Upper Danube catchment and Neckar catchment).

	Upper Danube[1]	**Neckar**[2]
Discretisation x, y [m]	1000	1000
Layers	4	9
Columns	425	146
Rows	430	181
Active cells	116702	82812
Observation wells	1222	254
Extraction wells	1787	1382
River cells	4163	1782
Transient model		
Simulation period length [years]	10-100	1 to 30
Temporal resolution (stress period length) [days]	1	1 to 10
Groundwater Recharge (1 x 1 km, daily)	Promet/SVAT[3]	HBV[4]

[1] for more details: Barthel et al. (2005), Barthel et al. (2007a)
[2] for more details: Jagelke and Barthel (2005)
[3] calculated by: physically based (Richards-Equation) Soil Vegetation Atmosphere Transfer Model based on Promet (Mauser, 1989)
[4] calculated by: conceptual hydrological model, HBV (Bergström. 1995) modified (Götzinger and Bardossy 2005, Götzinger et al., 2006)

3. Modelling Results

The two groundwater flow models were used to carry out different simulations for steady state and transient conditions according to Table 1. Transient simulations were carried out in both cases using input from various climate and socio-economic scenarios (mainly driven by groundwater recharge input, which was calculated different climate data input, Table 1). Fig. 4 and Fig. 5 show stationary results for both models in comparison to observed values. Fig. 6 shows transient model results for 9 observation wells in the Neckar catchment from a validation run.

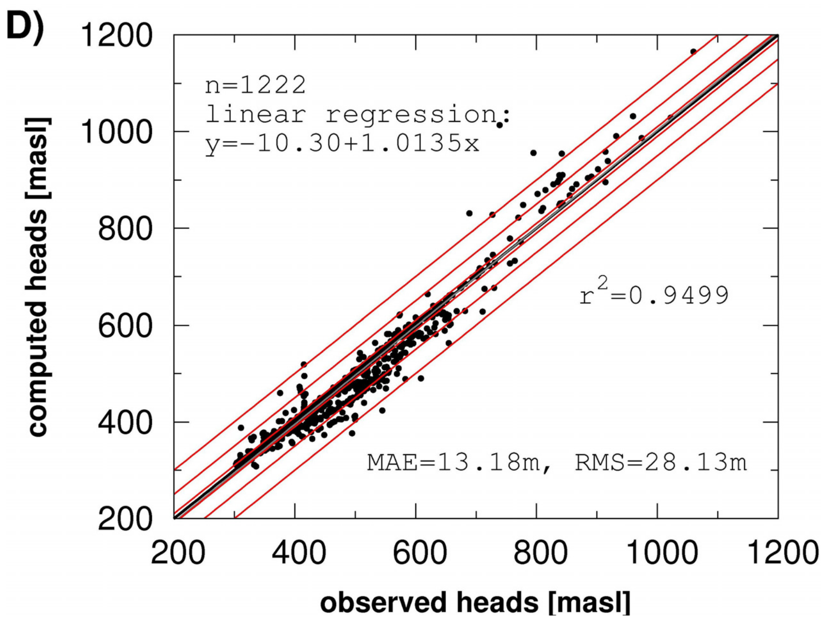

Fig. 4: Stationary model results: observed vs. computed for the Upper Danube catchment model.

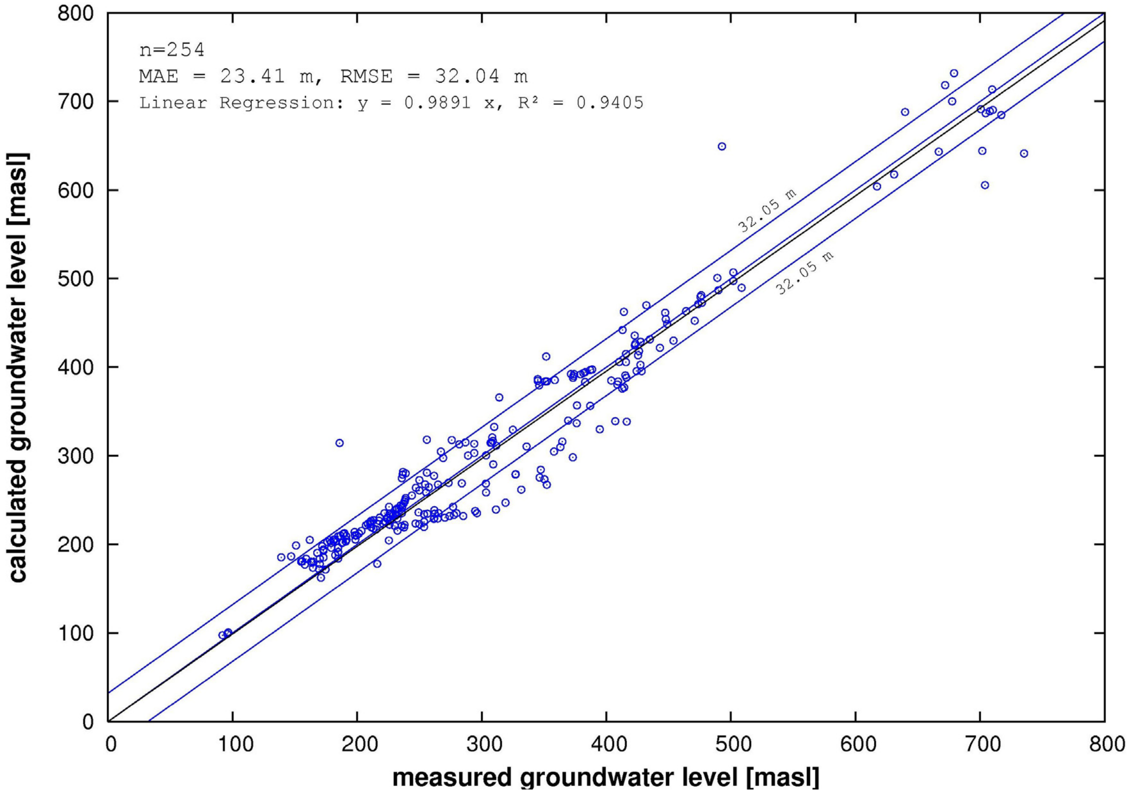

Fig. 5: Stationary model results: observed vs. computed for the Neckar catchment model.

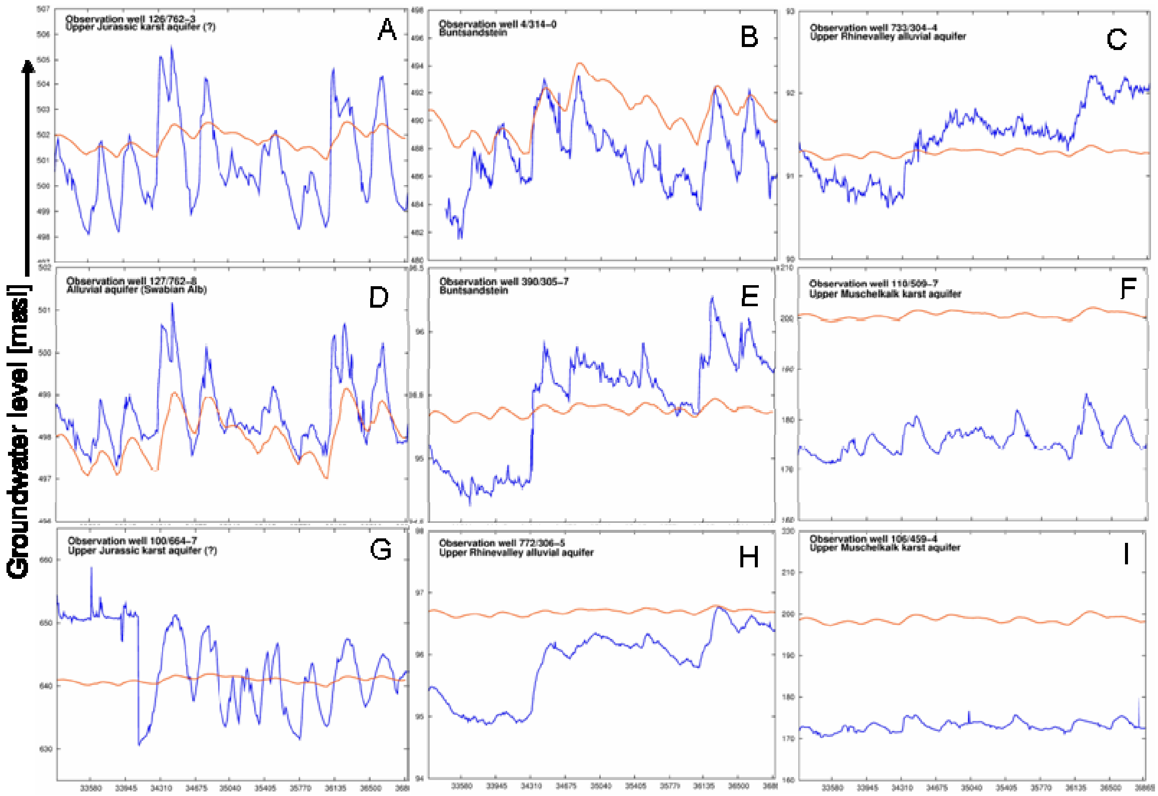

Fig. 6: Transient model results - validation: observed (blue line) vs. computed (red line) groundwater levels for 9 observation wells in different aquifers in the Neckar catchment (1991-2001).

Fig. 6 demonstrates impressively the differences of the model performance in different regions and different aquifers of the model. Each of the graphs would require a detailed discussion of local natural and model characteristics. Since this is not possible here, only a few aspects are summarized:

- the simulated heads follow the dynamics of the observed time series but in all cases the are dampened compared to the observed ones, i.e. have smaller amplitudes – a scaling effect due to the coarse discretisation
- absolute values can often not directly be compared since the topographic situation and the location of the well may lead to a shift of simulated versus measured groundwater levels (see Fig. 6F,H,I)
- Many observations are obviously influenced by human interventions such as change of withdrawal schemes, building or removal or weirs and other structures which lead to sudden changes of the well characteristics Fig. 6C,E,G,H. A specific problem in that case is that detailed data on withdrawal from wells is not available.

Fig. 7 finally shows transient results from the groundwater flow model from scenario simulations in the Upper Danube Catchment. Here three different scenarios are compared. The scenarios are described in more detail in Table 2). Fig. 7 demonstrates that the transient groundwater flow model of the Upper Danube catchment reacts reasonably to changes of groundwater recharge in put on average. Thereby the high dynamics of groundwater recharge (monthly and seasonal changes) are reflected in the behaviour of the groundwater heads with a delay of about one year and in a smoothed way.

Table 2: Climate scenarios used to calculate the results presented in Fig. 7

Scenario	Description	Comment
Business as usual	IPCC B2 type scenario	Only the first 33 years are shown
Optimistic	Observed data from 1970 to 2003 were used	Used for model validation; optimistic in the sense that all predictions are warmer than the conditions in this period
Pessimistic	An extremely dry "scenario" generated by simply combining the hottest and driest years from the 1970 to 2003 period	Rather unrealistic and not in accordance with IPCC!

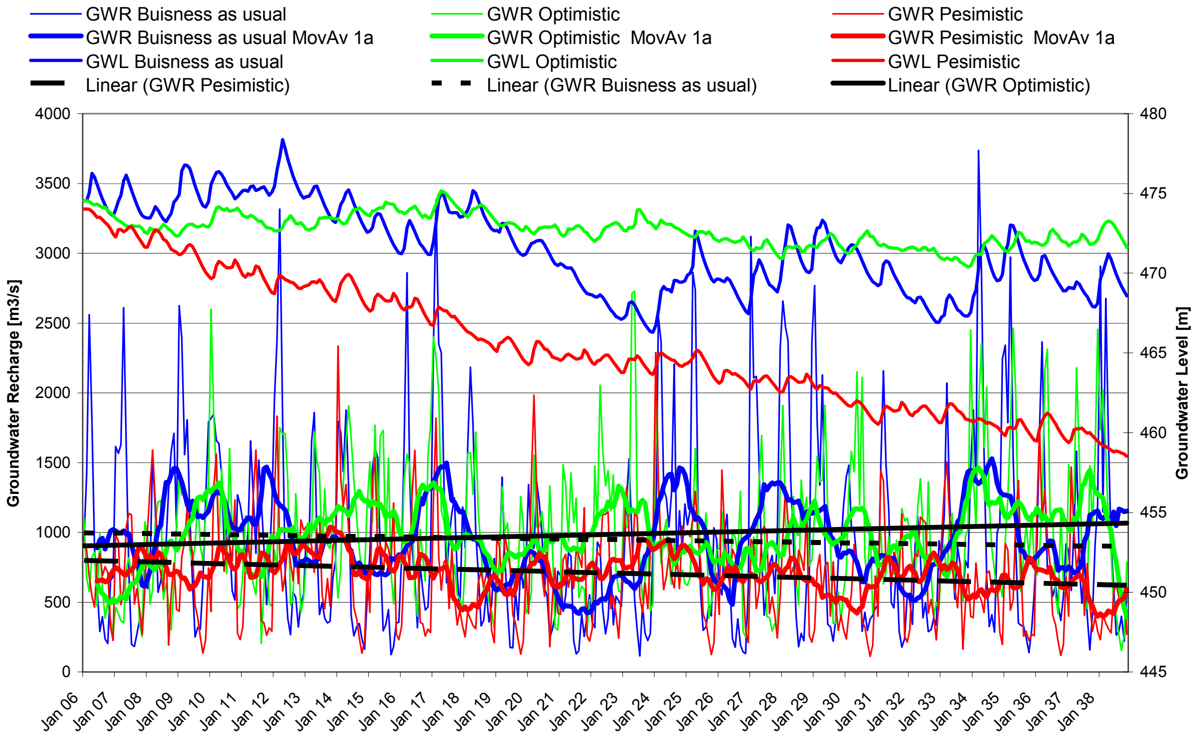

Fig. 7: Transient model results – scenario simulations: Mean monthly groundwater recharge (GWR) and groundwater levels (GWL) values averaged over the entire Upper Danube catchment for 3 different climate scenarios (Table 2); linear trends and moving averages (central) are shown for GWR.

It is obvious that this small selection of results from such large and complex models cannot meaningfully explain the modelling results in general. Here we summarize the most important common particularities of the results:

1) Qualitatively the modelling results from the Neckar and the Upper Danube Basin are quite similar (Fig. 4 and Fig. 5)
2) Model results are partly very good but also partly very bad (see Fig. 6). The reasons for these differences are regional and local particularities of the geology and geomorphology but can also be a result of data availability and heterogeneity, quality of the input data (groundwater recharge). The number of influencing factors is high such that an individual discussion for every single observation is necessary.
3) The results become more reliable and meaningful if they are aggregated spatially and temporally (Fig. 7).

4. Conclusions

Any experienced groundwater modeller will agree that meaningful groundwater flow modelling is very difficult for areas as large and complex as the Neckar and the Upper Danube catchment. Developing basin-scale groundwater models is tedious and challenging. If model geometry and parameterisation are carefully considered, numerically stable models can be created that perform reasonably well, if results are averaged on spatial and temporal scales. The results, however, should always be regarded as results of regional models, lacking the spatial and temporal details of local simulations, and, subsequently, the applicability to local problems. Data availability is an issue on the regional scale even in the well-investigated catchments of Germany. This can of course be stated for any groundwater model, but on the regional scale the amount and spatial distribution of available data is particularity problematic since regional models include the ‘less interesting parts’ with scarce data. A crucial aspect of regional models proves to be groundwater recharge (see Barthel (2006) for a more detailed discussion). It would be desirable to know much more about effective groundwater recharge (the part of the recharge that actually reaches the regional aquifers being modelled), interflow, baseflow and other immeasurable quantities.

In the Neckar catchment, regional groundwater problems can clearly benefit from a physically based 3D model (Barthel et al., 2007b). However, the data availability for model set up and parameterization is low in relation to the complexity of the area. Groundwater management problems are predominately local ones, but several regional tasks such as prediction of low flow periods under conditions of climate change are also present. In the Upper Danube catchment is particularly difficult to model since it combines a thin intensively distributed and highly efficient drainage network of alluvial porous aquifers (Wolf, 2006), intensively carstic terrains, crystalline rocks and an alpine mountain belt which makes up 30% of the area and receives 50% of the precipitation. Here, it is inevitable that mixed approaches must be employed, i.e. a combination of the deterministic numerical scheme in the stratified regions and conceptual approaches in the complex mountainous areas. Finally, in the Ouémé catchment regional groundwater flow modelling is especially problematic. Here the modeller has to deal with generally low data availability, partly unreliable data in combination with unfavourable hydrogeological conditions. But the most important aspect for groundwater flow modelling in the Ouémé basin is the fact, that groundwater management here must be mainly focussed on local issues which cannot be captured by regional models (see Barthel et al., 2007b).

As a general conclusion it can be stated that groundwater flow models on the regional scale in hydrogeologically complex regions are in many cases obviously not the only appropriate method to describe the groundwater system. The question of how to represent the groundwater resources meaningfully with respect to data availability and the existing management problems has to be discussed very thoroughly for any modelling area or catchment. It is not possible to give a final recommendation on which modelling concept is the most appropriate one in regional integrated modelling and management. Many of the considerations examined so far seem to lead to the conclusion that basin-wide 3D groundwater flow and transport models are very often not feasible or not applicable, even if in theory the present management tasks demand for such models. Arguments that could be produced to support this might be:

- On the regional scale, there will usually not be enough data, even in 'data-rich' regions
- On the regional scale, the complexity of groundwater systems increases to a degree where basin wide models are not feasible
- Efforts for model development and potential benefits and use are not balanced
- Groundwater related problems are often not regional scale problems, if they are, other model concepts (hydrological ones) can solve them equally well or better

On the other hand, there are arguments that support the opposite conclusion:

- Only a three-dimensional (3D) groundwater (GW) model can deal with different aquifers (vertically) and subsequently simulate (different) piezometric heads also of confined systems
- Only a 3D GW model can balance an aquifer system (area is not necessarily identical to a surface watershed!) meaningfully
- Only an integrated 3D GW model can include both groundwater levels *and* piezometric heads in the calibration

- Only a 3D GW model can quantify horizontal and vertical flow in the subsurface (direction and fluxes)
- 3D GW models are a good means for checking the plausibility of other models (water quality, hydrology, soil water balance etc.) because they can relate water balance terms to the reaction of the groundwater system (changing heads) directly in a process oriented way
- They can enhance the applicability of hydrological models in the field of water availability because only they can explain subsurface exchange fluxes between basins

It does not make sense to balance the arguments listed above in favour or against in an attempt to try to come to a final conclusion. Nevertheless, a couple of general recommendations are possible. The essential lessons can be learned from analysing the resulting models and the difficulties encountered during their development. The following issues were found to be decisive:

1. It is crucial to define the central objectives of modelling very clearly.
2. Data availability is very important. If the data availability is very low or data is available only in parts of the basin, a three-dimensional groundwater model should not be applied to the whole basin. It is not always preferable and necessary to use only one model concept to represent a basins groundwater system.
3. On the regional scale it is very important to create an appropriate model geometry which equally considers the natural conditions and the numerical requirements (Wolf, 2006).
4. Developing groundwater flow models on the regional scale requires pragmatic solutions rather than the implementation of complex, process-based state of the art modelling approaches.

In general we think that merely ‘hydraulic’ approaches based on volumes, flow rates and pressure data will not yield meaningful results on the regional scale. Models on this scale - which are usually characterized by a high degree of heterogeneity and relatively poor data availability - need to be constrained further by using any information that helps to determine the origin, the age and the fate of water in the hydrological cycle. Useful additional information can be the use of remote sensing data, but first and foremost the use of hydrochemical data, natural and artificial tracers and isotopes to determine groundwater age, recharge rates, recharge sources, groundwater surface water exchange rates and more.

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