The Role of Groundwater Recharge in Regional Scale Integrated Groundwater Flow Modelling

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Abstract: Using the example of two groundwater flow models of the Neckar and Upper Danube Catchments the role of groundwater recharge in regional scale integrated groundwater flow modelling is discussed. Both models are components of integrated management support systems and coupled to hydrological models of different types. For both models, groundwater recharge, which is calculated by the hydrological models forms the main input. The two case studies show that the underlying conceptual ideas of the groundwater recharge estimation have a major influence on the results of the groundwater models. It proves that the concepts of groundwater flow models and the concepts of hydrological models must be carefully adapted to form a consistent (free of gaps and overlaps) description of the hydrological cycle. More generally it can be shown that coupling of groundwater flow and hydrological models leads to results which are worse than the results of the respective individual models. On the other hand, an integrated approach provides more information than the single models alone; not only does it provide more than one measurable quantity for model calibration and validation; it also offers the opportunity to check the plausibility of internal state variables, the model structure and the conceptual base of the model.

Keywords: Groundwater Recharge, Groundwater Model, Hydrological Model, Coupling, Neckar, Danube, RIVERTWIN, GLOWA-Dabube

1. Introduction

Integrated water resources management (IWRM) is often concerned with problems on the river catchment scale (often > 10 000 km^2) where the impacts of climate change or human intervention usually affect all components of the hydrological cycle. Various interactions and interdependencies between different components exist and have to be considered in the attempt to meaningfully describe processes and to evaluate the consequences of human intervention. Groundwater plays a very important role as a resource in many parts of the world and therefore deserves special attention in integrated management. Groundwater flow models are the only means to meaningfully describe the effects of hydrological changes on the groundwater system. In contrary to (conceptual) hydrological models or water balance based modelling approaches, deterministic numerical 3D groundwater flow models can consider multiple aquifers, can describe horizontal as well as vertical flow, calculate flow direction and velocity, can quantitatively simulate groundwater discharge to surface waters at a specific location and, above all, provide hydraulic heads in different aquifers. For all kinds of groundwater related management questions, but in particular with respect to ecological issues, the mentioned capabilities of groundwater flow models are essential. However, the application of groundwater flow models on the *regional scale* in heterogeneous areas poses severe problems due to insufficient data availability, discretisation problems and numerical instability. Therefore regional scale groundwater flow models as the two presented here are still rare.

The present study deals with two regional scale integrated modelling projects (RIVERTWIN, Neckar catchment, Germany, 14 000 km^2; www.rivertwin.org and GLOWA-Danube, Upper Danube catchment, 77 000 km^2; www.glowa-danube.de). In both projects regional scale groundwater flow models with a horizontal discretisation of 1 x km were developed. The groundwater flow models are part of larger integrated decision support systems and coupled to several other models. The integration scheme is rather different in both projects and will not be discussed here. Descriptions of the integration approach can be found in Gaiser et al. (2007) and Ludwig et al. (2003). Fig. 1 shows the location of the two catchments.

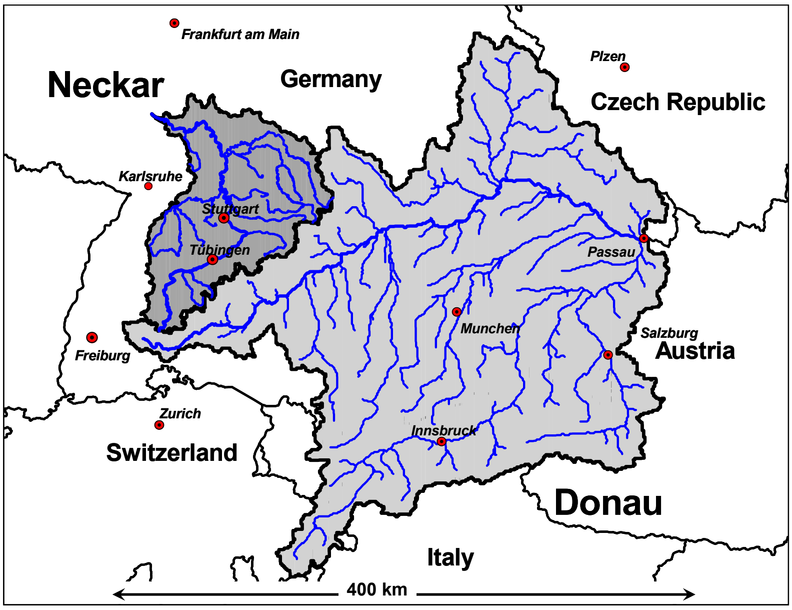

Fig. 1: Location of the Neckar catchment and the Upper Danube (‚Donau') catchment

In this paper, the focus is on the coupling of groundwater flow models with hydrological and hydraulic models, i.e. coupling of the groundwater system to the unsaturated zone and the surface water system. Important processes that connect the groundwater and the surface system (soil, unsaturated zone, surface waters) are groundwater recharge and baseflow (better: groundwater discharge). A closer look at these apparently well-defined terms reveals that the description and quantification of these processes depends on a number of factors. The quantity, spatial and temporal distribution of both recharge and baseflow depend on the scale, the context of modelling (objectives, integration), and the model concepts and on the specific conditions of the investigated area, including climate, topography, hydrogeology and others. Baseflow plays an important role in coupling groundwater flow to hydraulic and hydrological models. This paper, however, focuses on the groundwater recharge only. Conceptual problems of using baseflow as an exchange parameter are described in Barthel (2006).

A particularly significant issue we identified in the two modelling projects is the question of how to apply groundwater recharge as a boundary condition for the groundwater models. In both catchments, recharge calculated by coupled soil water balance or hydrological models is the most important boundary condition. It proves that the recharge calculated by the distributed conceptual models HBV and LARSIM in case of RIVERTWIN / Neckar or a physically based SVAT scheme in the case of GLOWA-Danube (Upper Danube) cannot be applied to the groundwater flow model *unmodified*. The main reason is that the groundwater flow models considers mainly regional scale aquifers which are partly located quite deep, the hydrological models are partly based on *soil* parameters which are determined on a 'local' scale (1 x 1 km grids) and represent properties of the subsurface only in a very shallow depth of 0 to 5 m).

In the following section (section 2), the models developed in these two case studies and their conceptual and numerical set-up are briefly presented as well as the different coupling strategies to hydrological and hydraulic models. Section 3 gives a more specific description of the problem of using groundwater recharge as a coupling process. In section 4 modelling results of the stand-alone groundwater models for steady-state and transient conditions are presented and discussed. Section 5 summarizes the major findings and considerations.

2. Problem Description

2.1 Conceptual inconsistencies and the role of terminology

For the purpose of this article, the hydrological cycle and its conceptual representation can be simplified to the situation shown on the right hand side of Fig. 2: a system comprising a hydrological ‘block’ (model) and a groundwater ‘block’ (model). In this article the focus is on the r.h.s. of Fig. 2. The main connecting processes and subsequently exchange parameters (variables[1]) are *groundwater recharge*, as the flux leaving the unsaturated part and entering the groundwater system, and *baseflow* as the flux leaving the groundwater and entering the surface water system[2]. This assumption leads to a simple and straight forward coupling principle. However, at a closer look it reveals that it heavily relies on the definitions of the terms it is founded on.

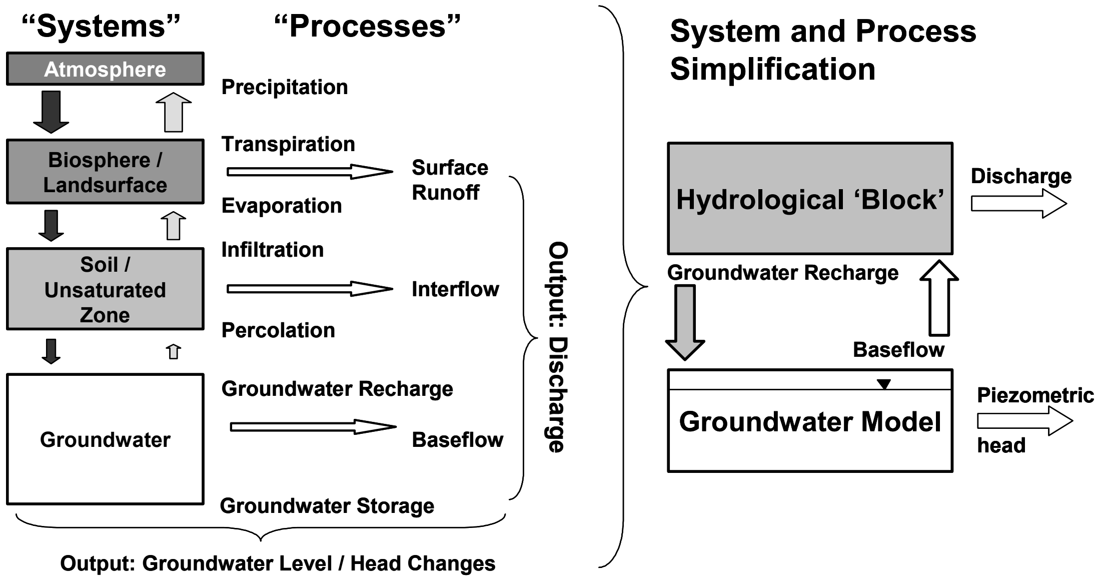

Fig. 2: Fundamental systems and processes that are typically considered when groundwater and surface water / unsaturated zone systems are coupled.

It is well known that neither groundwater recharge nor baseflow can be measured directly because it is largely unknown where and how these processes *exactly* take place. Consequently, these processes are inaccessible for measuring procedures on larger scales or cannot be clearly separated from others. Less well known is the fact that no common definition that would be meaningful in the context of large scale models exists for either of these terms. A hint to proof this is the existence of a large number of methods to determine groundwater recharge as well as baseflow. The methods to calculate groundwater recharge are conceptually very different and accordingly yield very different results. Groundwater recharge can be directly calculated using physically based approaches (unsaturated flow equations, tracers, chemistry, isotopes …) or indirectly using conceptual models (for an overview of state-of-the-art methods see: de Vries et al., 2002). One reason why so many different methods were established is the actuality of contrasting catchment characteristics and different data availability as well as different scales of application. At the same time, diverse approaches are the result of a different understanding of what recharge really is. Conflicting view points across different disciplines can be recognized. Two extreme interpretations can be identified:
Groundwater recharge is usually defined as the sum of all inflows to a groundwater system or aquifer. From the groundwater standpoint, this includes all inflows from above, from below and lateral inflows. Only under very specific conditions it is possible to measure or calculate all these recharge terms. Therefore even groundwater experts almost always reduce the recharge definition in practice to the inflows coming from above (precipitation, effluent rivers). But still their focus is usually on the

[1] Parameters and variables are terms that are used differently in different disciplines. Here both terms are used for variable values of physically defined quantities.
[2] We neglect here all fluxes in opposite directions since they play a minor role for the two case studies.

volume of water entering the *aquifer*. On the other hand, surface hydrologists and soil scientists usually suppose groundwater recharge to be the amount of water leaving the soil or root zone, since this is the domain they predominantly deal with (see Scanlon et al., 2002). The basic assumption here is: When water leaves the domain influenced by vegetation (roots) and evaporation (capillary rise etc.) vertically downwards, it will reach the groundwater eventually and must therefore be equivalent to groundwater recharge. Fig. 3 exemplifies these two contradictory views:

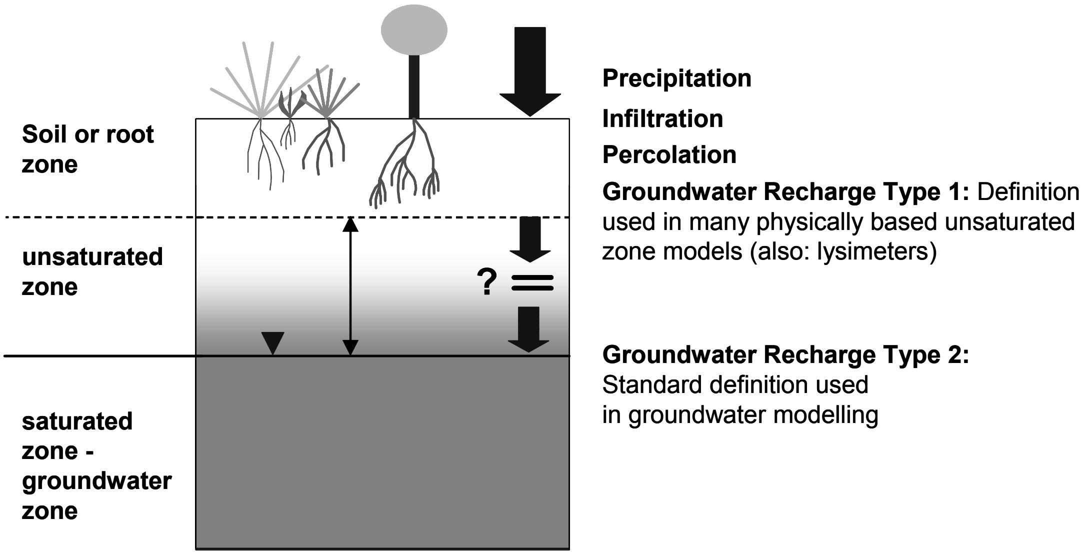

Fig. 3: Groundwater recharge - two contrary conceptual interpretations. Type 1: water leaving the root zone, Type 2: water entering the saturated zone.

According to Fig. 3, it would be valid to assume that groundwater recharge defined as ‘root zone percolation’ and groundwater recharge defined as ‘water entering the saturated zone’ describe the same quantities. This is only true if volumes are averaged over a longer period of time, since depending on the distance between the root zone bottom and the groundwater surface, a temporal delay occurs and flows are exclusively vertical. Fig. 3, however, shows a very specific situation with a shallow groundwater table (thickness of root zone and the total thickness of the unsaturated zone are of the same order of magnitude), a completely flat relief and homogenous, isotropic conditions. On a larger scale it is highly unlikely that conditions like this are realized everywhere in a catchment. On a large scale, relief will be present and the subsurface will usually be heterogeneous. Under such conditions, the scheme shown in Fig. 3 must be replaced with the scheme shown in Fig. 4.

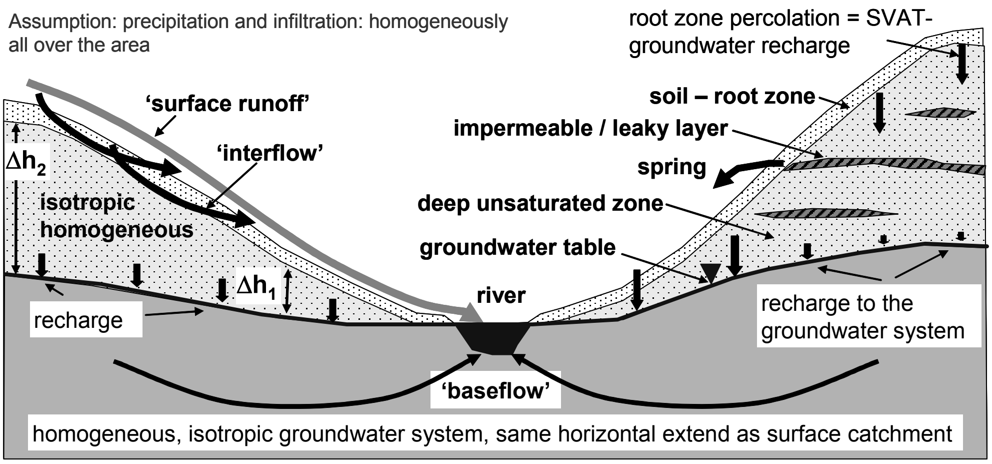

Fig. 4: More realistic (compared to Fig. 3) but still highly conceptual view of land surface, soil and groundwater processes.

Fig. 4 shows a still idealized, simplified situation but is more realistic with respect to formation of groundwater recharge. It becomes obvious that in an area with relief, the depth to the groundwater is a relevant factor for any transient model (Fig. 4, left side). Of even greater influence however are heterogeneities such as impermeable or less permeable layers that occur in the unsaturated part between root zone and groundwater (Fig. 4, right side). Such layers of lower permeability can be found everywhere. The greater the depth to the groundwater is, the more frequent and the more effective these zones of lower permeability usually are. They lead to the formation of saturated lenses (perched water) and subsequently to horizontal flow in the deeper unsaturated or partly saturated zone. Flow can be towards neighbouring catchments or can lead to the formation of springs. In either case, the flow does not reach the groundwater system and must therefore not be considered as groundwater recharge.
At this point, a definite gap in the two groundwater recharge definitions in Fig. 3 becomes apparent: If less permeable layers are present - or anisotropic, heterogeneous conditions in general -, the recharge actually reaching the groundwater system *must* be smaller than the recharge leaving the soil / root zone. The horizontal flow induced by the structures in the deep unsaturated zones can cause an overall loss of water from the catchment under investigation or become *interflow* (i.e., it reaches the surface water system without having been part of the groundwater system after a passage through the unsaturated zone).
The definition of groundwater, in particular in a modelling context is a highly scale-dependent one. Obviously not all perched or local aquifers or small saturated domains on the scale of some m^3 can be taken into account as groundwater in a regional groundwater flow model, even if the processes within this saturated domain are dominantly saturated flow processes. Fig. 5 demonstrates how a clear definition of groundwater as a saturated domain becomes questionable when the relevant scale changes over several orders of magnitude. It also shows how a seemingly clearly defined term such as groundwater recharge becomes ambiguous when regarded on different scales and in different contexts – depending on which aquifer is relevant for the specific problem. Finally it shows that recharge is not only a question of volume but also of time. Even if the recharge averaged over long periods might be the same, its temporal relation to climatic events (climate change) might be completely different.

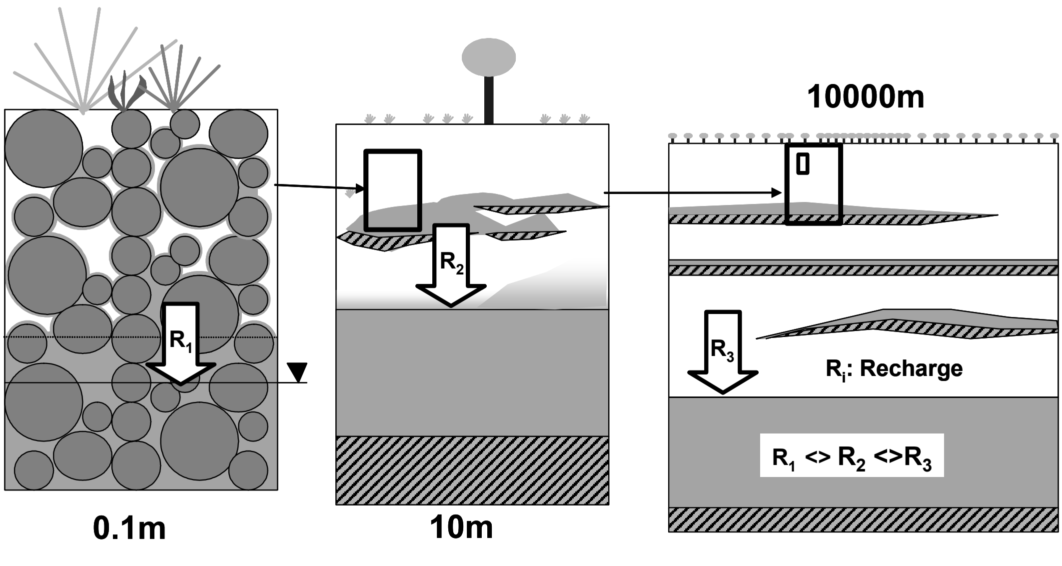

Fig. 5: Groundwater defined at different scales. The relevant definition in groundwater modelling depends highly on the size of the model domain and the discretisation. R_1 to R_3 show the relevant groundwater recharge for each of the relevant aquifers (scales).

At the same time it is widely believed amongst groundwater modellers that groundwater recharge is one of the least uncertain ‘physical’ input values for groundwater flow models. It is therefore very often used as a ‘fixed’ input (meaning no calibration takes place) whereas other values (hydraulic conductivity, leakage coefficients etc.) are changed and used for model calibration over wide ranges. This assumption forms a good basis for many groundwater flow models and is usually valid in all cases where recharge is aggregated over longer periods and larger areas. However, in regional groundwater flow modelling and in coupled systems the situation is different. Here recharge needs to be defined specifically for the regional aquifers that are considered in the numerical groundwater model. As on larger scales, aquifers of small vertical and horizontal extent can usually not be included in the models, it must be discussed how the actual natural recharge to those smaller scale aquifers can be treated in the numerical model.

2.2 Benefits of model coupling to reduce uncertainty

Having defined the problem of inconsistent process descriptions and different terminology in the previous section, the question, whether coupling of models on the regional scale makes sense at all needs to be addressed. As a result of the equifinality discussion in hydrological modelling (Beven and Binley, 1992), it has been proposed to reduce parameter uncertainty by using multi-response data or multi-criteria calibration. Kuczera and Mroczkowski (1998) observed that augmenting stream flow data with groundwater level data did not improve the identifiability of a nine parameter conceptual model. On the other hand, the use of stream salinity data in addition to stream flow data in the calibration process substantially reduced the parameter uncertainty in their study. Seibert (2000) discovered that the parameters of "HBV light" were significantly constrained when calibrated against stream flow and groundwater level data. For one of the catchments considered in the study the multi-criteria calibration even led to an improvement of the model structure.
The question of reducing uncertainty by coupling models must be seen in view of the conceptual problems described in section 2.1. Of course, if conceptual inconsistencies exist, coupled model results must be worse than results created by one model. However, model integration provides the possibility to check the plausibility of internal state variables, the model structure and the conceptual base of the model. Furthermore, an integrated approach provides more information than the single models alone; e.g. it provides more than one measurable quantity for model calibration and validation.

3. Case studies

3.1 Project backgrounds

The interdisciplinary research co-operation "GLOWA-Danube" (2001-2010) is developing the Global Change Decision Support System DSS "DANUBIA" to investigate the sustainability of future water resources management alternatives. The system equally considers the influence of natural changes in the ecosystem, such as climate change, and changes in human behaviour, e.g. changes in land use or water consumption (Ludwig et al., 2003). GLOWA-Danube is restricted to the analysis of the *Upper* Danube (Fig. 1; 77 000 km²), which is defined by the discharge gauge Achleiten near Passau in Germany. The Upper Danube is a mountainous catchment with altitudes ranging from ~300 to ~4 000 m.a.s.l. and a large foreland (precipitation: 650 to > 2 000 mm/a, evaporation: 450-550 mm/a, discharge: 150-1 600 mm/a, average annual temperature: -4.8 to +9°C). DANUBIA is a fully-coupled system that is comprised of 16 individual models to describe all compartments of the hydrological cycle (natural and socioeconomic) of the Upper Danube catchment. For further details on GLOWA-Danube in general see Mauser & Strasser (2005), for details on DANUBIA see Barth et al. (2004). The groundwater flow model is described by Barthel et al. (2005).
RIVERTWIN aims at adjusting, testing and implementing an integrated regional model for the strategic planning of water resources management in twinned river basins under contrasting ecological, social and economic conditions. The results of a model chain are loosely coupled by well-defined interfaces in MOSDEW (MOdel for Sustainable DEvelopment of Water Resources). Three river basins with contrasting ecological, social and economic conditions were selected: 1. The Neckar basin (Fig. 1; Germany, Central Europe); 2. The Ouémé basin (Benin, West Africa); 3. The Chirchik basin (Uzbekistan, Central Asia). Gaiser et al. (2007) give a more detailed overview. Results of RIVERTWIN plus the possibility to choose results from different models and scenario simulations are provided in further detail on the internet under http://mapserver.ilpoe.uni-stuttgart.de/rivertwin/index.php. The Neckar basin, located in south-western Germany, covers an area of about 14 000 km^2. The elevation in the catchment varies from ~100 m.a.s.l at the catchment outlet to about 1 000 m a.s.l. The climate is humid with an annual precipitation of 950 mm.

3.2 Groundwater flow models

For modelling the groundwater flow, the physically-based 3D finite difference groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) is used in both catchments. MODFLOW is based on the horizontal and vertical discretisation of the modelling domain and solves the groundwater flow equation - derived from the law of conservation of mass and Darcy's law - for each discrete point in space and time taking into consideration recharge, as well as pumping and drainage from the given groundwater system. It enables the simulation of leakage between adjacent aquifers and can reproduce flow paths in all three spatial directions. The main characteristics of the two groundwater flow models are summarized 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]	30	1 to 30
Temporal resolution (stress period length) [days]	1	1 to 10

1 for more details: Barthel et al., 2005, Barthel et al. 2007)

2 for more details: Jagelke and Barthel (2005)

3.3 Hydrological models in RIVERTWIN

In RIVERTWIN, a modified version of the semi-distributed conceptual HBV model (Bergström, 1995) was developed (Götzinger and Bardossy, 2005, 2007). HBV has conceptual routines for calculating soil moisture and runoff generation, runoff concentration within the sub catchment, and flood routing of the discharge in the river network. The main modification of the version used in this study is that the runoff generation and concentration routines are fully distributed on a 1 x 1 km raster. Fig. 7 shows the general model structure of the distributed HBV model and additionally the coupling strategy to MODFLOW.

Land use (Landsat 1993, resolution 30 m), soil (Bodenübersichtskarte 200, scale 1:200 000) and topographic data (resolution 50 m) were aggregated to a uniform grid resolution (1 x 1 km). Precipitation and temperature data were interpolated by external drift kriging from observation station data. Discharge data from 58 gauging stations was used for model evaluation. All data was provided by the State Institute for Environmental Protection Baden-Württemberg.

3.4 Model coupling and integration

As mentioned before, both models are integrated in larger management support system. The coupling approaches are thereby quite different: In DANUBIA all models are fully coupled, i.e. they run at the same time and exchange parameters at run time. MOSDEW follows a loosely coupled approach, where models run individually and exchange time series of results. As the temporal aspects of model coupling are of minor importance in the context of the present article, Fig. 6 shows and compares only the general conceptual ideas behind the coupling and the main exchange parameters. It should be pointed out that in both systems the spatial discretisation of all models belonging to the "hydrological complex" is 1 x1 km.

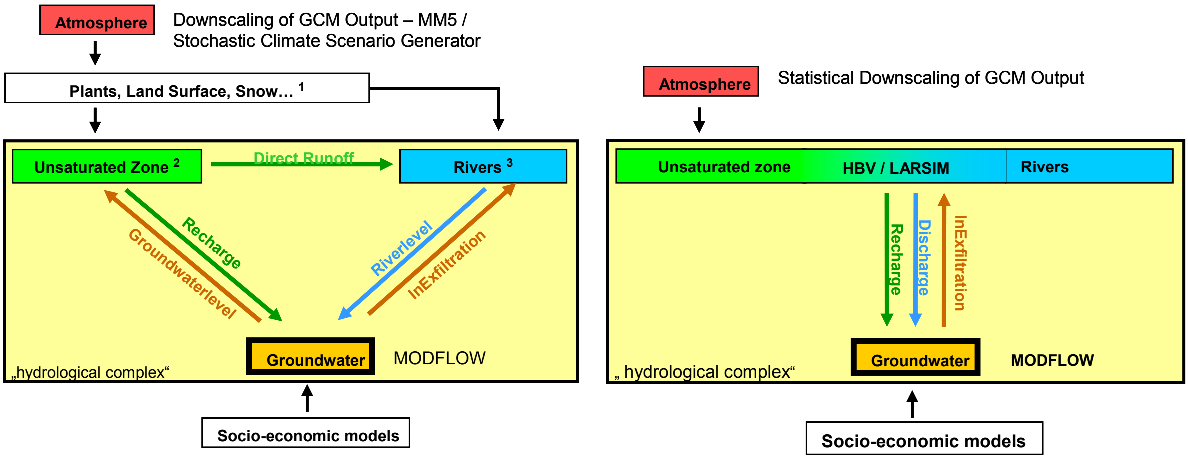

Fig. 6: Coupling (highly schematic) in GLOWA-Danube/DANUBIA (left) and RIVERTWIN / MOSDEW (right)

Fig. 7 visualizes in more detail the chosen integration strategy in the Neckar basin. Geographic and climatic data provide the parameters and driving forces of the hydrological model, HBV (modified; Bergström, 1995, Götzinger and Bárdossy, 2005), which calculates, besides the discharge components, groundwater recharge rates at a high spatial resolution (1 x 1 km cells). The coupling approach is described in more detail in Götzinger et al. (2006). The HBV model used in this study varies from the original version in the discretisation and process description of the soil module; square grid cells are used as primary hydrological units and all processes except the groundwater reservoir are run on this raster. As shown in Fig. 7, the groundwater recharge is simulated by a variable percolation rate from the soil storage directly to the groundwater reservoir. Groundwater recharge from the HBV model then serves as input to the groundwater model which simulates groundwater levels and groundwater runoff in the stream network, which can be used in the hydrological model to complete the discharge.

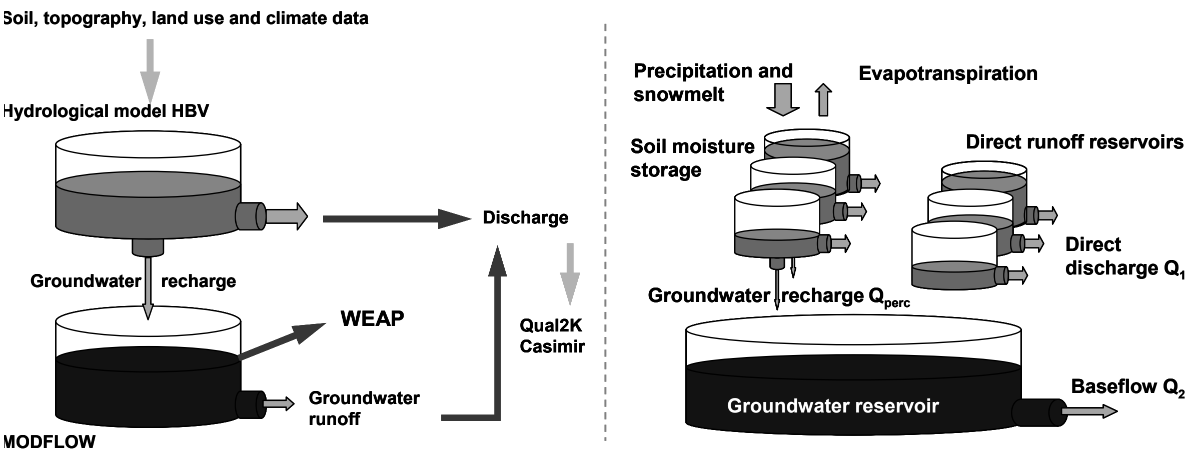

Fig. 7: The groundwater - surface water coupling strategy in RIVERTWIN and the representation of the main processes in the modified HBV model

4. Results

In order to meet the length requirements for this article, results are presented here mainly for the Neckar catchment models. The results for the Upper Danube catchment with regard to the context of this paper show the same characteristics. Furthermore, in the context of this paper, groundwater modelling calibration results (i.e. simulated groundwater heads compared to observed groundwater levels) are not in the centre of focus. Instead it is more interesting to compare the results of simulation runs carried out with the groundwater model that are based on different groundwater recharge inputs. In RIVERTWIN (Neckar) a coupling strategy was mainly developed for MODFLOW and HBV. However, three different models or data sets respectively for groundwater recharge were available.

HBV (as described above), LARSIM (Bremicker, 2000) and TRAIN-GWN (results provided by LUBW[3]) developed by Armbruster (2002)) allow for the simulation of daily groundwater recharge. All results show a high spatial variability which is dominated by climate, land use and soil type (see Fig. 8). Fig. 8 shows two interesting aspects:

a) TRAIN-GWN, a physically based SVAT-scheme (Soil Vegetation Atmosphere Transfer) shows a significantly higher average recharge for the whole basin than the conceptual models HBV and LARSIM
b) The spatial patterns of groundwater recharge distribution are quite different, even for HBV and LARSIM that produce almost similar average values.

It should be pointed out, that TRAIN-GWN considers the hydrogeological conditions of the catchment best, whereas HBV is based mainly on soil properties and LARSIM largely ignores physical catchment characteristic. All approaches were calibrated using measured river discharges.

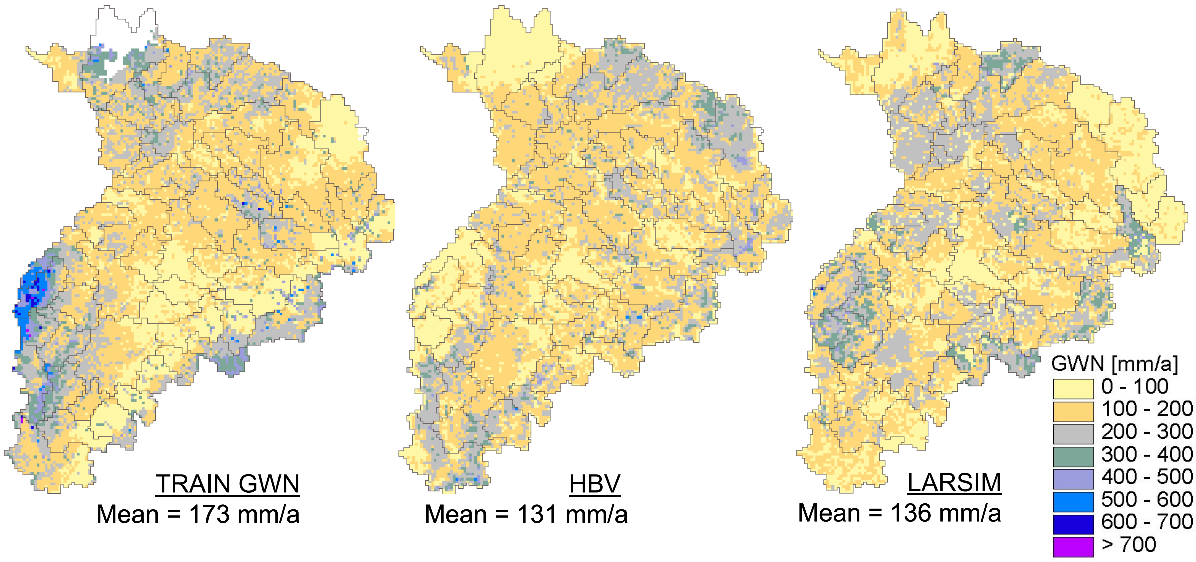

Fig. 8: Spatially distributed recharge averages for the period 1991 to 2001 calculated by three different hydrological models (HBV, LARSIM, TRAIN)

As the objective of the projects presented here is to make suggestions for future management under conditions of climate change, it is interesting to see what the influence of different groundwater recharge inputs on the prediction of groundwater level and baseflow is. Fig. 9 shows the results of different simulations. First, groundwater recharge calculated by HBV for two different climate scenarios (see Gaiser et al., in print for further details) was applied to the groundwater flow model. Second, groundwater recharge calculated by HBV and LARSIM for the same climate scenario was used as boundary condition for the groundwater flow model. Even if the average recharge for the whole basin for HBV and LARSIM differs only slightly (Fig. 8), the effects on groundwater levels and baseflow are significant and outweigh the influence of different to some degree. This is a result of the different spatial and temporal distribution of the groundwater recharge of the two hydrological models.

5. Conclusions

In this contribution the role of groundwater recharge as a boundary condition for groundwater flow models was described. Regional scale groundwater flow modelling is required in IWRM and global change research. It is assumed here that groundwater recharge is an output of external calculations (hydrological models) and forms an input (time variant boundary condition) for groundwater flow models. On a more theoretical basis it was argued that the definition and meaning of groundwater recharge depends on disciplinary view points and additionally on the scale, discretisation and context of modelling.

[3] LUBW: state institute for environmental protection, (Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg)

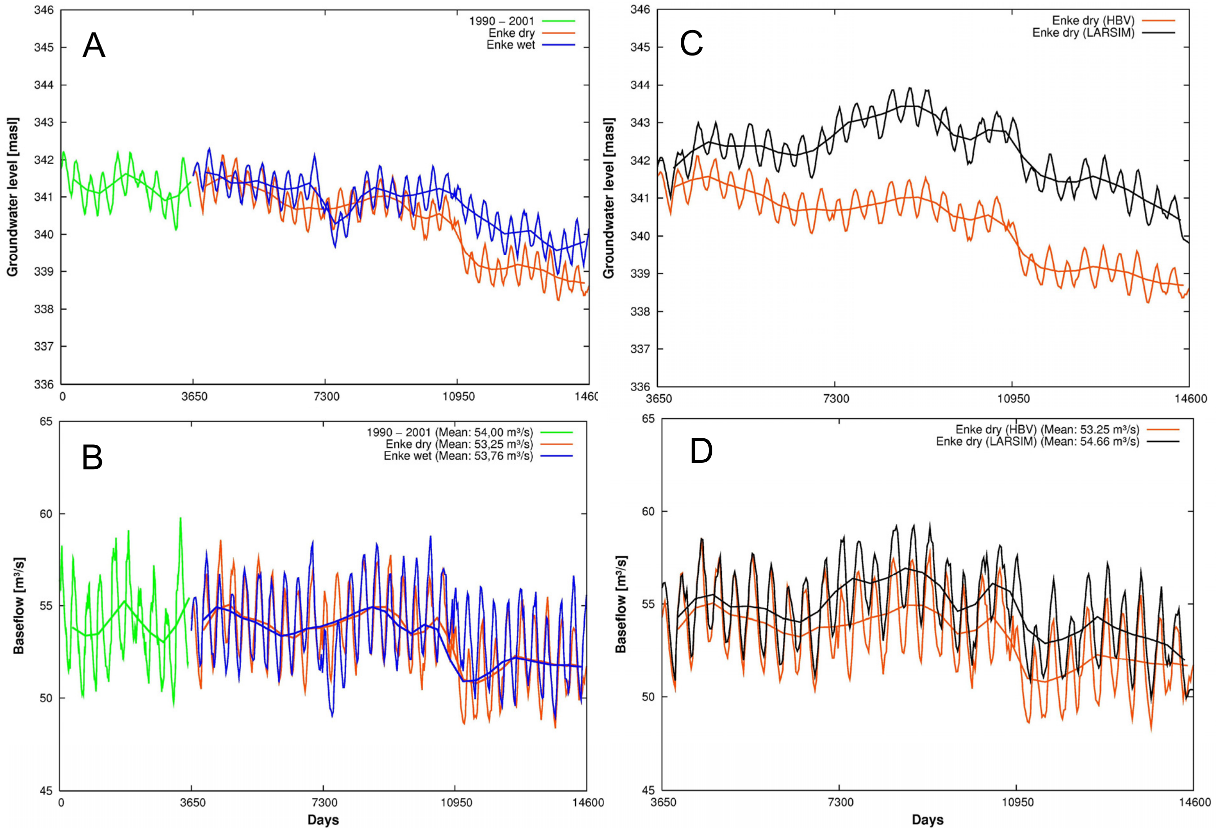

Fig. 9: A and B: groundwater level and baseflow calculated using HBV for two different climate scenarios and the validation period (1991-2000). C and D: groundwater level and baseflow calculated using HBV and LARSIM for the same climate scenario

Practically the Neckar case study showed that the use of groundwater recharge input from different hydrological models has a larger effect on the groundwater levels and baseflow than the use of different climate scenarios. For the predictive capabilities of the models used to evaluate the impacts of global climate change on groundwater resources this is a quite unsatisfactory result.
One source of severe problems in using groundwater recharge calculated by hydrological models might be the fact that the unsaturated zone - in particularly on the regional scale - can be of considerable thickness (up to 100 m and more). What is defined as the 'unsaturated zone' depends always on the scale of the problem (see Fig. 5). In a coupled regional model, the groundwater recharge, commonly defined as the amount of water percolating through the plant-influenced soil zone, has therefore to be determined considering the processes in the deep unsaturated zone, where horizontal unsaturated/saturated flow can predominate. On the regional scale, local 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.
It is very important to point out that groundwater recharge, which is often said to be the most reliable input to groundwater flow models is something that needs a lot of attention when used in integrated systems on a regional scale. Holistic conceptual approaches to describe the processes of the hydrological cycle above at and below land surface are needed to come to meaningful models that have the required predictive capabilities required to cope with management problems under condition of Global change.

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References

Armbruster V (2002) Grundwasserneubildung in Baden-Württemberg, Freiburger Schriften zu Hydrologie, Band 17, Freiburg i. Br.

Barth M, Hennicker R, Kraus A, Ludwig M (2004) DANUBIA: An Integrative Simulation System for Global Research in the Upper Danube Basin. Cybernetics and Systems 35(7-8): 639-666

Barthel R, Mauser W, Braun J (2007) Integrated modelling of global change effects on the water cycle in the upper Danube catchment (Germany) - the groundwater management perspective. IN: J J Carillo & M A Ortega (Editors) Groundwater flow understanding from local to regional scale, International Association of Hydrogeologists, Selected Papers on Hydrogeology, Vol 12, pp47-72.

Barthel R (2006) Common problematic aspects of coupling hydrological models with groundwater flow models on the river catchment scale. - Advances in Geosciences, 9, 63-71

Barthel R, Rojanschi V, Wolf J, Braun J (2005) Large-scale water resources management within the framework of GLOWA-Danube. Part A: The groundwater model. Physics and Chemistry of the Earth 30: 372-382.

Bergström, S (1995) The HBV model. In: Singh, V.P., (Ed.): Computer Models of Watershed Hydrology, Water Resources Pub., Littleton, CO, pp. 443-476,.

Beven K, Binley A (1992) The Future of Distributed Models: Model Calibration and Uncertainty Prediction Hydrological Processes, 6, 279-298

Bremicker M (2000) Das Wasserhaushaltsmodell LARSIM – Modellgrundlagen und Anwendungsbeispiele. Freiburger Schriften zur Hydrologie, Institute for Hydrology, University of Freiburg, Vol. 11.

de Vries J J, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. - Hydrogeology Journal 10, 5-17.

Gaiser T, Printz A, Schwarz von Raumer H G, Götzinger J, Dukhovny V A, Barthel R, Sorokin A, Tuchin A, Kiourtsidis C, Ganoulis I, Stahr K (2007) Development of a regional model for integrated management of water resources at the basin scale. Physics and Chemistry of the Earth, corrected proof, available online: doi:10.1016/j.pce.2007.04.018

Götzinger J, Bárdossy A (2007) Comparison of four regionalisation methods for a distributed hydrological model. Journal of Hydrology, 333, 2-4, 374-384

Götzinger J, Bárdossy A (2005) Integration and calibration of a conceptual rainfall-runoff model in the framework of a decision support system for river basin management, Adv. Geosci., 5, 1–5.

Götzinger J, Jagelke J, Barthel R, Bárdossy A (2006) Integration of water balance models in RIVERTWIN, Advances in Geosciences, 9, 85-91.

Jagelke J, Barthel R (2005) Conceptualization and implementation of a regional groundwater model for the Neckar catchment in the framework of an integrated regional model, Advances in Geosciences, 5, 105-111.

Kuczera G, Mroczkowski, M (1998) Assessment of hydrologic parameter uncertainty and the worth of multiresponse data Water Resources Research, 34, 1481-1490

Ludwig R, Mauser W, Niemeyer S, Colgan A, Stolz R, Escher-Vetter H, Kuhn M, Reichstein M, Tenhunen J, Kraus A, Ludwig M, Barth M, Hennicker R (2003) Web-based modelling of energy, water and matter fluxes to support decision making in mesoscale catchments – the integrative perspective of GLOWA-Danube, Physics and Chemistry of the Earth 28: 621-634

Mauser W, Strasser U (2005) Statusreport GLOWA-Danube Integrative Techniques, Szenarios and Strategies Regarding Global Change of the Water Cycle. - http://www.glowa-danube.de/PDF/reports/statusreport_phase2.pdf

McDonald M G, Harbaugh A W (1988) A modular three-dimensional finite-difference ground-water flow model. Technical report, U.S. Geol. Survey, Reston, VA. USA.

Scanlon B R, Healy R W, Cook P G (2002) Choosing appropriate techniques for quantifying groundwater recharge. - Hydrogeology Journal (2002) 10:18–39.

Seibert J (2000) Multi-criteria calibration of a conceptual runoff model using a genetic algorithm, Hydrology and Earth System Sciences, 4(2), 215-224.

Wolf J (2006) Räumlich differenzierte Modellierung der Grundwasserströmung alluvialer Aquifere für mesoskalige Einzugsgebiete. - Institutes für Wasserbau der Universität Stuttgart, Heft 148, PhD Thesis, 133p.