Integrated modelling and assessment of regional groundwater resources in Germany and Benin, West Africa

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Abstract Regional groundwater flow models (Neckar catchment, Germany, 14 000 km^2, and Southern Ouémé Basin, Benin, 11 000 km^2) were developed within the framework of the integrated management project 'RIVERTWIN' (www.rivertwin.org). Both models were evaluated with respect to the question of whether the chosen modelling approaches are appropriate in view of the existing management problems, data availability and the hydrogeological and hydrological conditions. In the case of the Ouémé, the groundwater related problems are highly localized and therefore cannot be addressed by regional models in a meaningful way. Data scarcity and complex, unfavourable geological conditions (crystalline rocks, discontinuous aquifers) support the conclusion that numerical 3D groundwater flow models are currently not helpful to manage groundwater related management problems in the Ouémé basin. In the Neckar catchment, regional groundwater problems could clearly benefit from a physically based 3D model since the hydrogeological system is strictly stratified. As a general conclusion it can be stated that the suitable representation of groundwater resources must be thoroughly discussed for any new integrated water resources management problem.

Keywords: Groundwater Management, Neckar Catchment, Benin, Regional Model, Climate Change

1. Introduction

Since groundwater serves as the major drinking water resource and is key for irrigation purposes in many parts of the world, the appropriate representation of groundwater systems play a major role in Integrated Water Resources Management (IWRM). IWRM, according to the World Summit on Sustainable Development at Johannesburg in 2002, must be dedicated to the regional (basin) scale in order to consider the dependencies between different uses of water, different impacts, stakeholders and different areas within catchments (Rahaman & Varis, 2005). Climate change should also be studied at the regional scale to bridge the gap between global circulation models, IPCC reports and local groundwater related problems. Investigation, modelling and assessment of groundwater resources on the regional scale is particularly challenging since many important groundwater processes are strongly influenced by local heterogeneities. It is therefore crucial to determine the appropriate balance between the requirements of regional IWRM and the description of local conditions in a meaningful way. Today, sustainable management of water and land resources is widely understood as an integrative, cross-border task, in particular in Global Change research. The impacts of climate change cannot be evaluated meaningfully without considering, for example, land use changes (subsequent or independent) or other natural and socio-economic developments. Evaluating and predicting the availability of groundwater quantity and quality under changing boundary conditions (scenarios) is a central task in Integrated Water Resources Management (IWRM) (Villholth, 2006, Holman, 2006). Models are an essential part of such integrated projects. As fully integrated, i.e. holistic model concepts do not exist, integration is often achieved by the coupling of existing disciplinary models (Barthel, 2006).

1.1. Project Background

There are two research activities that the authors are currently involved in, and that the theoretical considerations presented here mainly stem from. The GLOWA-Initiative funded by the German Ministry of Research and Education (www.glowa.org, www.glowa-danube.de, BMBF, 2005, Barthel et al., 2008) and the European Community financed RIVERTWIN project (www.rivertwin.org, Gaiser

et al., 2008) use the idea of integrated research and link it to the investigation of the effects of Global Change on the hydrological cycle and to the development of an integrated model based Decision Support Systems (DSS). There are an increasing number of similar or related projects that follow the same idea. Examples would be the WAVES project (Gaiser et al., 2003), projects carried out under the framework of the HELP initiative of the UNESCO (UNESCO, 2001) and projects within the framework of the Sixth Framework Programme - Priority 1.1.6.3 - Global Change and Ecosystems (http://ec.europa.eu/).
Within the framework of the integrated management project 'RIVERTWIN' (www.rivertwin.org) two regional groundwater flow models (Neckar catchment, Germany, 14 000 km^2, and Southern Ouémé Basin, Benin, 11 000 km^2) were developed. Both 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) are appropriate in view of the existing management problems in the catchments, the data availability and the hydrogeological and hydrological conditions in the basins. RIVERTWIN supports the goals of the EU Global Water Initiative (www.euwi.org), which proposes to apply the principles of the European Water Framework Directive (WFD) to other continents. The integrated regional model MOSDEW (Model for Sustainable Development of Water Resources) was developed accordingly. Three basins with areas between 14 000 and 40 000 km^2 and with contrasting ecological, social and economic conditions were selected:
Neckar basin (Germany, Central Europe, temperate-humid);
Ouémé basin (Benin, West Africa, tropical-subhumid);
Chirchik basin (Uzbekistan, Central Asia, continental-semiarid) – not dealt with in this paper.

2. Study Areas

2.1 Neckar Basin

The Neckar catchment is located in the state of Baden-Württemberg in the south-western part of Germany (Fig.1). It covers an area of 14,000 km² with a population of 5 million. The area belongs to the most densely populated and most intensively industrialized region of Germany. The terrain elevation varies between 90 and 975 m above sea level. The climate in the Neckar catchment is moderate. Due to the heterogeneity of the relief, rainfall and evaporation vary strongly. The rainfall ranges between less than 800 and 2000mm/a, the average evapotranspiration is 550 mm/a. According to (Armbruster 2002), the mean groundwater recharge is 158 mm/a and varies spatially from 3 to 643 mm/a for the period 1980 to 2002.

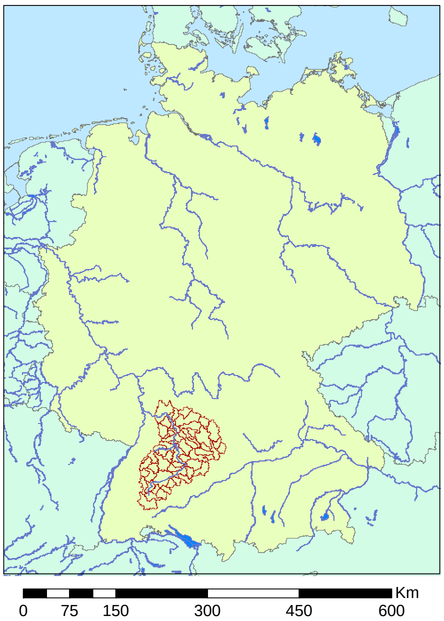

Fig. 1 Location of the Neckar basin in Germany .

In the Neckar catchment, gently dipping, quasi-horizontal, consolidated fractured and karstic sedimentary aquifers (Fig. 1) with poor to medium hydraulic properties are present over the entire basin area (i.e. aquifers with a hydraulic conductivity K= 10^{-5} to 10^{-4} m/s and an effective porosity n_e = 0.01 to 0.05, for more details see Jagelke and Barthel, 2005). The natural groundwater quality is fairly good apart from high TDS values in certain evaporitic formations.

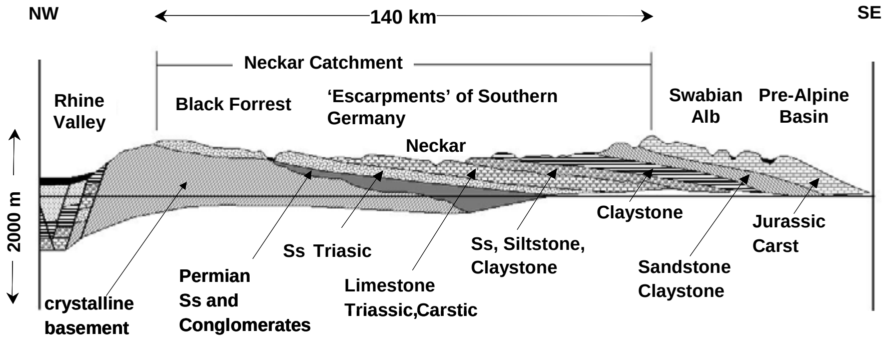

Fig. 2: Geology of the Neckar basin – cross section

About 50% of the people living in the Neckar catchment are supplied with drinking water from inter-basin groundwater resources. Water shortages in regions with groundwater or water scarcity have been overcome by the long distance water supply infrastructure created in the 1960s (UVM, 2001). Alongside domestic consumption, inter-basin groundwater is also used intensively for industrial purposes, whereas irrigation does not take place in significant quantities (yet is increasing). Groundwater quantity becomes increasingly an issue with respect to ecological and economic aspects. In dry periods, when river discharge is mainly groundwater runoff, river levels can decrease to an extent that damages the fauna and flora of the surface water bodies, limits navigation capacity on the river and reduces the output of hydropower plants (KLIWA, 2006).
Also of concern are various groundwater quality issues. Apart from many point source polluters and old contaminated sites, diffusive inputs of mainly fertilizers, and other chemicals used in agriculture pose problems on groundwater-based water supply systems. Nitrate values are generally decreasing, but certain hotspots with values well over 50 mg/l remain (LfU, 2005).

2.2 Ouémé Catchment

About 89 % of the Ouémé catchment is located in Benin, ~10 % in Nigeria and ~1 % in Togo. The climate of Benin is of typical monsoon type which is characteristic for the large sub-humid Savannah zones of the world. Average annual temperatures are approximately 27°C, with temperature amplitudes of 5-6°C. The Southern Sudan Savannah zone tends to be semi-arid and there is a single summer rainy season in Northern and Central Benin; a subequatorial moist savannah zone (Guinea-Savannah) can be found in Central and Southern Benin, and the humid subequatorial zone in the South, which both show bimodal rainfall patterns Stahr (2000). The mean annual aerial precipitation is about 1200 mm.
The hydrogeology of the Upper and Lower Ouémé basin differs significantly. In the Northern part a precambrian crystalline basement (migmatite, gneiss, granite, extrusives) and precambrian quarzites and micashists are covered by a tertiary regolith and a lateritic weathering zone ('saprolite'). Major faults dominate the tectonic situation in the northern part. Unweathered crystalline rocks with few fractures make poor aquifers. However, weathered granites and other SiO_2-rich crystalline rocks can show a relatively high porosity and permeability. Fracture zones often lead to medium to high hydraulic conductivities in the vicinity of faults. Altogether, zones of improved hydraulic properties (i.e. potential aquifers) are limited to the thin (0 to ~ 20 m) weathered zone and to the intensively fractured zones in the vicinity of major faults. The resulting groundwater bodies usually have a low storage capacity and are not connected to each other. Therefore they lack the continuity that would be required for regional groundwater flow modelling. The southern coastal basin is dominated by weakly consolidated sand, sandstone, clay and claystones. The variability of the vertical sequence is high. The sand dominated parts form good aquifers. Stratification leads to the formation of several separated, confined to leaky aquifer systems. Some of them are connected to the ocean.

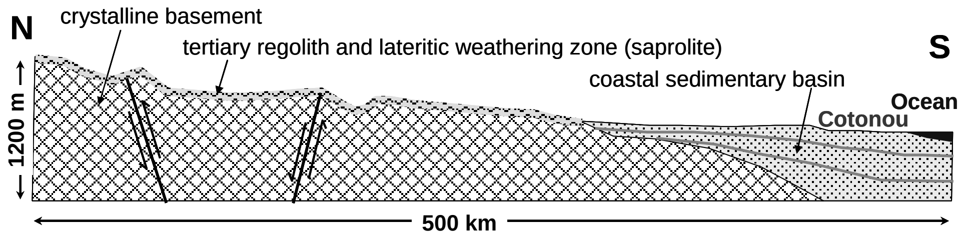

Fig. 3: General geological situation of the Ouémé basin – cross-section

In the Ouémé basin groundwater is an important resource, yet information on its reliability in terms of quantity and quality is still lacking. Availability and accessibility are distributed unevenly both spatially and temporally. In view of these statements a demand for research in the following fields can be determined:

From a hydrogeological and hydrological point of view, it remains unclear whether the current use of groundwater has already reached its limits with respect to availability, sustainability, quality (health) issues and economically feasible solutions, or whether a better understanding of hydrological and hydrogeological processes, better groundwater management and more efficient technical solutions might be able to enhance the situation substantially. Subsequently, from a socio-economic point of view, it remains unclear if it is at all possible to use groundwater to develop more secure agricultural and economic systems and to which degree better management can support current population development.

3. Groundwater Modelling

3.1 Modelling Approaches

In order to simulate the groundwater flow system with emphasis on groundwater-surface water interactions MODFLOW2000 (Harbaugh et al., 2000) was chosen. It is a deterministic numerical model concept, based on the horizontal and vertical discretisation of the modelling domain which solves the groundwater flow equation for each cell (Figure 4). In the Neckar basin the MODFLOW Drain Package enables the simulation of infiltration into the rivers and thereby a coupling to surface water models (Figure 5). Exfiltration from the rivers into the aquifers can be largely neglected in the Neckar basin because it plays a minor role on the regional scale under the conditions of the semi-humid to humid climate. In the Ouémé the River Package is used to enable both in- and exfiltration. It should be mentioned that numerical stability and water balance errors are a big issue and influence the choice of a parameterisation of boundary conditions in both models.

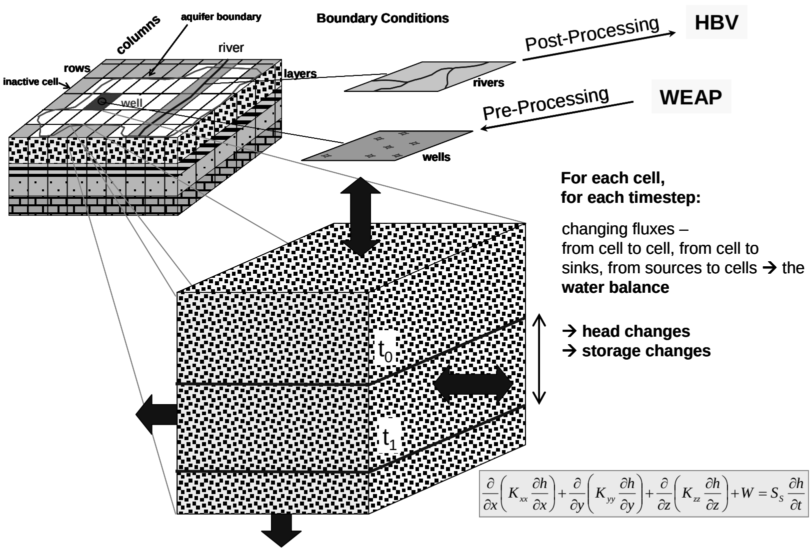

Fig. 4: Principle of the MODFLOW 3D finite difference modelling concept and the provided results. In the integrated system, recharge and extraction rates are calculated by partner models: The

hydrological model HBV (Götzinger et al., 2006) and the water planning model WEAP (Yates, et al., 2005)

3.2 Modelling Results

3.2.1 Neckar basin

The individual calibration of the groundwater model was started with an adjustment of the initially defined hydraulic conductivity and leakage coefficients for steady state conditions using an average groundwater recharge for the period from 1991 to 2001 (data from Armbruster, 2002). The recharge data was provided by the Baden-Wurttemberg state authorities and had a spatial resolution of 1 * 1 km which is compliant with the model discretisation. In the steady state calibration, the hydraulic conductivity within pre-assigned geological zones was adjusted applying the Gauss-Marquardt-Levenberg algorithm such that the sum of the squared differences between the measured and the model-generated groundwater levels was minimized. The calibration was carried out until both the groundwater levels in the different aquifers as well as the water balance showed a satisfactory calibration result along with a plausible groundwater flow field. The RMSE of ~32 m (Fig. 5) seems large but the following aspects must be considered: a) the model is steady state but the observations stem from different years and different seasons, b) on a 1 * 1 km grid in a domain with a relatively steep relief and groundwater gradients, deviations between observed and calculated values (MODFLOW: cell centred) must be attributed partly to scale effects; c) it is not always clear in which aquifer the piezometers are filtered, and, even if this is explicitly stated, it is not clear if the assignment of the geological formations (the hydrostratigraphy is far more diverse than any model could represent) to one of the nine model layers was chosen ‘correctly’. Finally it should be mentioned that the steady state model is just used as a means to determine initial conditions and a reasonable initial parameterisation for the subsequent transient model. The goal, according to the idea of RIVERTWIN, is to carry out transient scenario-based simulations where the absolute values of groundwater levels are less interesting than the relative changes compared to the past average conditions and the general trends.

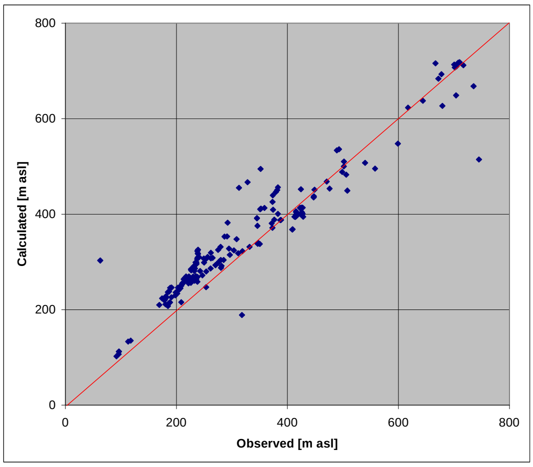

Fig 5: Results of the steady state calibration.

Starting with the field-adjusted parameters in the steady-state calibration, a transient calibration for a chosen reference year (2000) was carried out using the groundwater recharge calculated by HBV. The hydraulic conductivity and the specific storage were further modified manually. The objectives here were: (1) to reproduce measured groundwater hydrographs (2) to calculate a reasonable baseflow into the rivers coinciding with the total discharge calculated by the surface water model and (3) to get a reasonable water balance (inflow, outflow, and storage). A discussion of measured versus calculated groundwater level time-series is beyond the scope of this article because single piezometers mainly display local phenomena and, at best, typical behaviour of an aquifer in a certain part of the basin.

3.2.2 Ouémé basin

A crucial aspect of groundwater modelling in the Ouémé basin – apart from the unfavourable hydrogeological conditions – is data availability. For example, data exist for about 960 drilled wells in the model domain (~ 2700 in the Ouémé catchment, ~4700 in Benin). However, details are problematic, which is a consequence of how and when this data was collected. Most of the wells were drilled in the 1980s and 1990s with the aim to provide water to the people and not to provide scientific base data. Static head data was measured only once, after drilling and before a pumping test. From this, errors in the range of 1 to more than 10 m can arise. Elevation values for most of the wells are missing and location data is obviously not very accurate, which is proven by the fact that up to eight wells with different geological characteristics can have exactly the same x and y coordinates. The static heads for wells with the same coordinates can vary in a range of up to 40 m. Given the additional problem that in 95% of the wells the elevation must be derived from a DEM (90m resolution, SRTM) and the head data is given as a drawdown (m below surface), it becomes immediately clear that it is almost impossible to relate the data to a common datum (m.a.s.l.). Any comparison of measured against calculated or any interpolation of well head data to derive piezometric surfaces is therefore error-prone

The situation in the southern part of the model domain is far more diverse than the vertical discretisation of the model. The observed values therefore represent sub-scale information which might not be correctly reflected by the much coarser vertical discretisation of the model. On the other hand, there is not enough data available to increase the vertical spatial resolution of the regional model any further. In the transition zone between sedimentary and crystalline part, where the sedimentary aquifers are thin, it remains often unclear which aquifer is actually tapped. In the northern part finally, wells obviously tap disconnected local groundwater systems. Therefore good matches using the given vertical and horizontal spatial discretisation are not possible.

Thus, the calibration results shown in Fig. 6 are not at all satisfactory. It would be possible to enhance these results by adjusting the hydraulic parameters and boundary conditions. However, in view of the quality of the data and the unfavourable hydrogeological conditions this effort seems not to be justified firstly because of the many unknowns (groundwater recharge, groundwater surface water interactions etc.) and secondly because a clear demand and a goal for such a model was not defined yet. The consequences of these considerations are further discussed in section along with recommendations for future work.

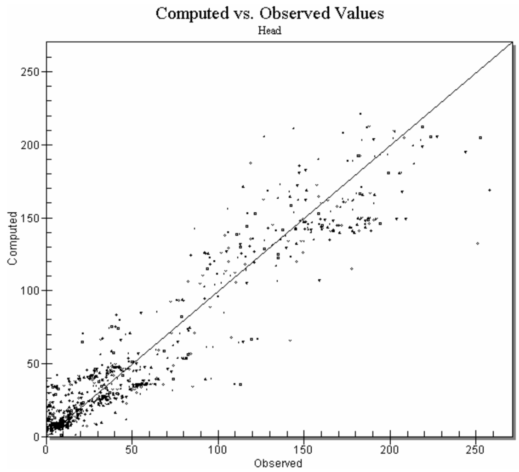

Fig. 6: Results of a steady state calibration of the Ouémé basin groundwater flow model. The diagram combines the results of all four aquifers. All values are in m.a.s.l.

2. Conclusions

The evaluation of the two models shows that groundwater flow modelling on the regional scale is problematic. Due to data scarcity and the required coarse discretisation the results become very inaccurate on the local scale. Thus the results of regional scale models can only be applied to regional scale problems. It must therefore be discussed whether such regional scale problems exist and if the use of numerical 3D models is appropriate. Regional scale models are in general better suited for long term tasks such as the regional evaluation of climate change, where trends and relative developments are needed rather than very accurate absolute values of, e.g. groundwater levels.

It could be shown that neither the model in the well-investigated, data rich basin in Western Europe, with its highly developed water related infrastructure, nor the model in the hydrogeologically less well-known and less developed basin in Western Africa provide results that are fully applicable to the main regional management tasks. In the case of the Ouémé, the groundwater related problems are foremost of local character and therefore cannot be addressed by regional models in a meaningful way. Data scarcity and complex, unfavourable geological conditions (crystalline rocks, discontinuous aquifers) support the conclusion that numerical 3D groundwater flow models are currently not helpful to manage groundwater related management problems in the Ouémé basin. A better understanding of regional hydrological surface and subsurface processes is required first. Methods for a reliable estimation of groundwater recharge and subsequently groundwater availability were identified as the most urgently needed tool for meaningful groundwater management in view of climatic, demographic and land use change. In the Neckar catchment the results of the analysis are less pronounced; here regional groundwater problems could clearly benefit from a physically based 3D model since the hydrogeological system is strictly stratified with several important aquifers in the vertical sequence. As a general conclusion it can be stated that regional scale groundwater flow modelling concepts are difficult to integrate in management systems and cannot easily be transferred from one basin to another. Thus the question of how to represent the groundwater resources appropriately has to be discussed very thoroughly for any new integrated water resources management problem.

A more comprehensive description and analysis of this project is provided in Barthel et al. (2008). In addition to the modelling study presented here, an integrated assessment of groundwater resources in Benin, West Africa which was performed to show the practical implications of the aforementioned model comparison for groundwater resources management on the regional scale. The assessment included a spatial analysis of groundwater relevant parameters taken from more than 4000 wells stored in a countrywide water database (BDI - Banque des Données Intégrée) and an estimation of the spatial and temporal distribution of groundwater recharge using a modified version of the hydrological model HBV. Additionally, a socio-economic assessment of the impacts of groundwater availability and accessibility on national health issues as well as an assessment of groundwater development costs was carried out. The results of this study are presented in Barthel et al. (in press).

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References

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

Barthel R, Mauser W, Braun J (2008) 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, Jagelke, J, Gaiser, T, Printz, A & Götzinger, J (2008) Aspects of choosing appropriate concepts for modelling groundwater resources in regional Integrated Water Resources Management – Examples from the Neckar (Germany) and Ouémé catchment (Benin). - Physics and Chemistry of the Earth, Parts A/B/C Volume 33, Issues 1-2, 2008, Pages 92-114

Barthel, R, Sonneveld, B G J S, Götzinger, J, Keyzer, M A, Pande, S, Printz, A & Gaiser, T (in press) Integrated Assessment of Groundwater Resources in the Ouémé Basin, Benin, West Africa. - Physics and Chemistry of the Earth

BMBF (ed.) (2005) GLOWA Global Change in the Hydrological Cycle - Status Report 2005, 158 p, http://www.glowa-danube.de/PDF/reports/statusreport_phase2.pdf

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 (2008): Development of a regional model for integrated management of water resources at the basin scale. - Physics and Chemistry of the Earth, Parts A/B/C, Volume 33, Issues 1-2, 2008, Pages 175-182

Gaiser, T, Krol, M., Frischkorn, H, Araujo, J C de (2003): Global Change and Regional Impacts Water Availability and Vulnerability of Ecosystems an Society in the Semi-Arid Northeast of Brazil. – 428p., ISBN: 3-540-43824-6, Springer –Berlin.

Harbaugh, A W, Banta, E R , Hill, M C and McDonald, M G (2000) MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model - User Guide to Modularization Concepts and the Ground-Water Flow Process". - U.S. Geological Survey, Open-File Report 00-92

Holman, I P (2006) Climate change impacts on groundwater recharge - uncertainty, shortcomings, and the way forward? Hydrogeology Journal 14: 637–647

Jagelke, J. and 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.

KLIWA (ed.) (2006) Regionale Klimaszenarien für Süddeutschland. Abschätzung der Auswirkungen auf den Wasserhaushalt. KLIWA Berichte 9, ISBN 3–88251–305–5.

LfU (2005) (Landesanstalt für Umweltschutz Baden-Württemberg, ed.) Grundwasserüberwachungsprogramm - Ergebnisse der Beprobung 2004, Karlsruhe

Rahaman, M M & Varis, O 2005. Integrated water resources management: evolution, prospects and future challenges. Sustainability: Science, Practice, & Policy 1(1):15-21.

UNESCO (2001) The design and implementation strategy of the HELP initiative. - IHP-V, Technical Documents in Hydrology, No. 44, UNESCO, Paris.

UVM (ed.) (2001) Beeinflussung der Wasserführung im Neckareinzugsgebiet durch Wasserüberleitungen. – Siedlungswasserwirtschaft: 18, 78p; Karlsruhe 2001, Umweltministerium Baden-Württemberg, Karlsruhe.

Villholth, K G (2006) Groundwater assessment and management: implications and opportunities of globalization Hydrogeology Journal 14: 330–339

Yates, D, Sieber J, Purkey D and Huber-Lee A (2005) WEAP21--A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 1, Model Characteristics. - Water International, 30, 487-500.