23nd CONFERENCE OF THE DANUBE COUNTRIES ON THE HYDROLOGICAL FORECASTING AND HYDROLOGICAL BASES OF WATER MANAGEMENT
28- 31. August 2006 Belgrade – Republic of Serbia

USING THE DANUBIA DECISION SUPPORT SYSTEM TO IDENTIFY CLIMATE CHANGE EFFECTS ON GROUNDWATER MANAGEMENT PERSPECTIVES

A. Trifkovic[1], R. Barthel[1], D. Nickel[1], W. Mauser[2] , U. Strasser[2], R. Ludwig[3], W. Willems[4], B. Frueh[5]

[1]Institute of Hydraulic Engineering (IWS), Universitaet Stuttgart, Pfaffenwaldring 61, D-70569 Stuttgart, Germany, ++49 711 685-65771,
roland.barthel@iws.uni-stuttgart.de

[2]Faculty for Geosciences, Ludwig-Maximilians University (LMU)
w.mauser@iggf.geo.uni-muenchen.de

[3]Institute for Geography, University of Kiel, Germany

[4]Institute for Applied Water Resources Management and Geoinformatics, IAWG - Ottobrunn, Germany

[5]Institute for Atmospheric Physics, University of Mainz, Germany

Abstract

Within the GLOWA initiative of the German Ministry of Research and Education, the research project 'GLOWA-Danube' aims at the development of new water resource management modelling technologies that integrate natural and socio-economic sciences in assessment of Global Change consequences. For this reason, natural science (meteorology, hydrology, hydro-geology, plant ecology, glaciology, remote sensing, computer science) and socio-economic science (agricultural and environmental economy, environmental psychology and tourism) research groups from different German institutions have developed the decision support system DANUBIA.

This decision support system for integrative environmental modelling is based on 16 object-oriented, spatially distributed and raster-based sub-components that represent disciplinary models for the description of the various water related processes. Based on the scenarios of future Global Change, the DANUBIA system models water cycle related processes in order to provide support to decision makers by simulating the impacts of different potential water resources management strategies. 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.

This paper describes the framework of GLOWA-Danube project and the developed decision support system DANUBIA with a focus on two models developed by the Universitaet Stuttgart. These two sub-models 'Groundwater' and 'WaterSupply' form together the Groundwater Management complex of DANUBIA and can be used to illustrate the applied concept for integrative modelling of natural and socio-economic phenomena and processes., Some of the results and potential applications just as well as some of the problems, constraints and difficulties in connection with the development of Groundwater Management complex are presented.

Keywords: Global Change, Integrated Water Management, Groundwater, Water Supply

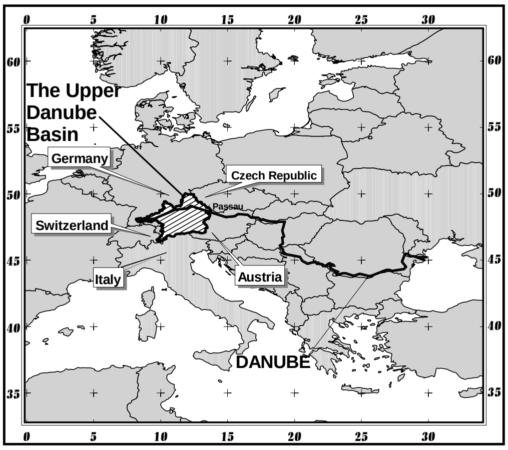
Introduction

Integrated approaches for modelling and forecasting physical, social, economic, and political processes related to the hydrological cycle, in particular with regards to Global Change, have recently gained worldwide attention, both with administrative authorities and in the research community. A functional understanding of the processes related to the water cycle and the influence of human societies upon these, has been recognized as crucial for the sustainable management of water. Due to the existence of many mutual interconnections among different natural processes and human activities, sectoral science approaches are neither capable of understanding the complex interactions between nature, water and man nor of developing methods for a sustainable water resource management. Furthermore, proactive watershed management aiming at a sustainable use of the water resources heavily relies on the development of possible future management scenarios and more reliable assessment of their impacts. To date, no commonly accepted modelling approaches are available to integratively describe the complex interactions between natural and social processes in the hydrological cycle. The lack of successful integration concepts is the result of large differences in the way the various disciplines formalize and describe their understanding of the respective processes. These differences in terms and concepts, comprehension and methodology lead to sectoral approaches for solving separate parts of the task, and hence provide no reliable basis for simulating recursive and interactive scenarios of future development.

As a consequence of increasing intensity of water use and water-related conflicts and at the same time, of rapid progress in the science of system analysis, modelling, simulation and optimization, just as well as of the development of novel computer technologies for data processing, analysis and visualisation a Decision Support Systems (DSS) have taken a leading role in providing necessary information for management of complex systems. Many examples of DSS can be found in the literature and many projects in this regard have been carried out. These approaches usually deal with isolated water-related problems and little effort has gone into making this scientific material available as part of practical planning or management tools for public policy makers at the regional level. The objective of GLOWA-Danube is to provide new modelling technologies to overcome this discrepancy and provide a common basis for scientific analysis and planning practices.

The Upper Danube Basin

Within the GLOWA-initiative (Global Change of the Water Cycle, www.glowa.org, funded by the German Ministry of Research and Education (BMBF, 2002; BMBF, 2005), that address the manifold consequences of Global Change on regional water resources, the Upper Danube watershed (Figure 1) was selected as a representative mesoscale test site in the temperate mid-latitudes.



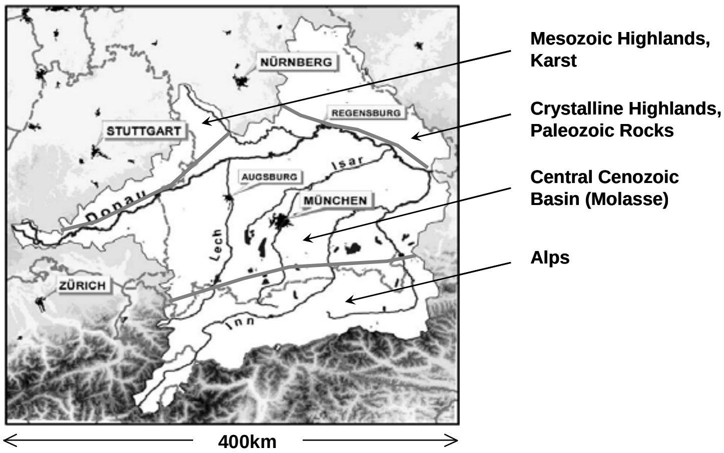


Fig. 1: The location of the upper Danube Basin in central Europe

Fig. 2: The Upper Danube Catchment. gauge Passau

GLOWA-Danube concentrates in the analysis of the Upper Danube (A~77.000 km²), which is defined by the discharge gauge Achleiten near Passau in Germany (Figure 2). The Upper Danube is a mountainous catchment with altitudes ranging from 287 to 4049 m a.s.l. and a large foreland (Figure 2). This introduces strong geographic, meteorological and socio-economic gradients (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, sources of income changing from industry and services to agriculture and tourism). The highly fragmented land cover and land-use is mostly determined by human intervention. Forestry and agricultural use of differing intensity (grassland, farmland) dominate, whereby climatic disadvantages in terms of high precipitation and low temperatures limit the present agricultural potential in various parts of the catchment (Mauser and Barthel, 2004).

The Upper Danube is densely populated with approximately 8 million inhabitants. A large part of the water for the water supply of the larger cities and industry originates in the pre-alpine region and in the Alps. The most important industrial agglomeration areas are Munich (1.2 Mio inhabitants), Augsburg (260.000), Ingolstadt (115.000) and the “chemical triangle” Burghausen. Drinking water use together with energy production, navigation and flood protection in Upper Danube are already judged as a very complex task. In addition, water from the catchment area of the Upper Danube is exported into the catchment of the River Rhine and increasing demand for water during the course of a more intense and more coordinated water use in Europe will even put a larger pressure to water export. Such pressures on water management in the Upper Danube make the assessment of ecological and socio-economic effects of water use and hence the limits to environmentally sound water use primary important tasks.

The Decision Support System Danubia

GLOWA-Danube comprises a university-based network of experts combining water-related competence in the fields of engineering, natural and social sciences (Mauser & Ludwig 2002, Ludwig et al. 2003). The project consists of the following disciplinary research groups which cover the essential modules in GLOWA-Danube: Coordination and GIS, Remote Sensing - Hydrology, Meteorology, Water Resources Management - Groundwater, Water Resources Management - Surface Waters, Plant Ecology, Environmental Psychology, Environmental Economics, Agricultural Economics, Glaciology, Remote Sensing - Meteorology, Tourism Research and Computer Sciences. A valid integration of all disciplines involved in GLOWA-Danube is crucial for the creation of a successful decision support system DANUBIA. In order to avoid deficiencies in common for models that consist of sub-models from different disciplines, such as high sophistication and specialisation in the discipline core on the account of exchange parameters or boundary conditions (often kept constant or are described in a simplified way), an integrative technique has been developed and applied (Mauser & Ludwig 2002). In the following only the modelling, spatial and temporal concepts applied in this integrative approach will be shortly presented.

Object orientation of the DANUBIA system is its prime modelling characteristic. Within DANUBIA each sub-model is regarded as an independent object with certain well defined public functionalities and a private modelling core. It model the water related processes from its competence area and exchange results with other sub-models. The delineation of core competences was based on the multilateral discussions of the contributing disciplines and provide for a consistent description of all physical and socio-economic processes, where each process is modelled exactly once. At the same time, the object oriented concept provide for a possibility of ease exchange of expertise among groups by using the offered public methods and parameters. Consequently, the entire project is profiting most from each single discipline's expertise, while avoiding unnecessary simplifications or redundant modelling of the same processes. Additionally, the well established advantages of object oriented modelling like inheritance and simple reuse of existing implementations contribute to a successful application within DANUBIA (Strasser 2005).

From a spatial point of view, a common problem that affects all research disciplines involved in coupled systems, such as DANUBIA, arises from the fact that the processes to be modelled have their main focus on different spatial scales. This scale discrepancy is often a cause of instable and low model performance. In order to avoid and overcome this drawback, as a basic spatial unit for all processes described in the DANUBIA a 1*1 km Process Pixels (Proxels) are adapted. Proxels are the basic building blocks of DANUBIA and consist of a pixel (picture element) in the form of a cube, in which processes occur (Tenhunen et al., 1999). The proxel concept is schematically represented in Figure 3.

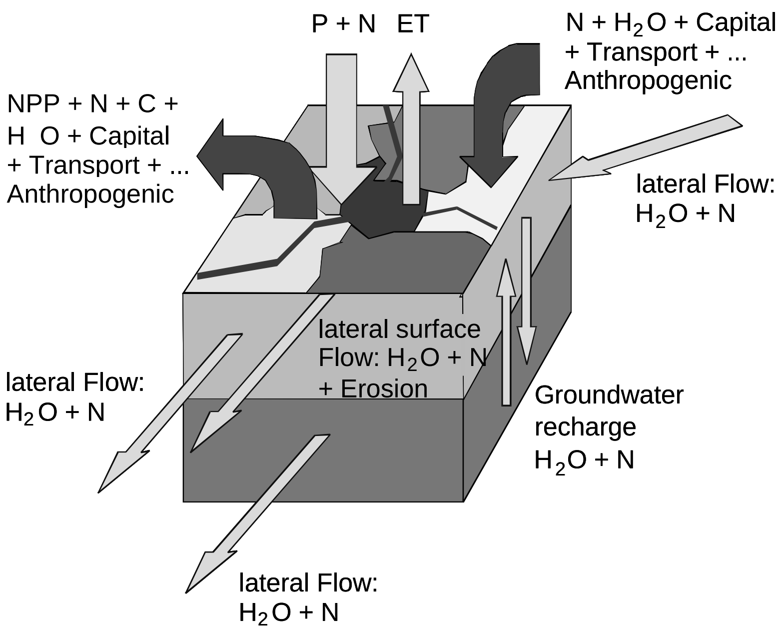


Fig. 3: Schematic raster based modelling in DANUBIA on the proxel basis (Ludwig et al., 2003)

Discretisation of time is an equally complex issue in the fully-coupled integrated model DANUBIA. Whereas a common spatial discretisation could be agreed on, model time steps must differ from model to model (15 minutes to one year). One main reason for this is that simulating very slow processes such as economic development with short times steps would result in an undesirable redundancy and low overall performance. On the other hand, processes that depend strictly on seasonally and diurnally varying parameters can not be reasonably treated using large time steps. Technically the problem of different time scales is solved using a 'market place' concept. Each model puts exchange variables that are needed by another model as an input in a 'public space'. Making an exchange variable 'public' is called 'commiting'. It is important to make sure that data is only committed upon the time it becomes valid and only stays 'public' as long as it is valid. This is technically relatively simple but conceptually difficult if exporting and importing models simulate processes on different time scales. Depending on the individual processes aggregation and dis-aggregation of values is necessary whereby aggregation is usually simple (e.g. a monthly average of the respective diurnal values) and dis-aggregation is more difficult. How this is treated depends strongly on the sensitivity of models towards the exchange variables in question but also on feedback loops between two or even more models (Barthel et al. 2004).

Groundwater Management in DANUBIA

Groundwater management according to worldwide or European standards such as the ones stated in the European Water Framework Directive has two main objectives: to provide water in sufficient quantity and quality to different consumers and at the same time to maintain and guarantee good qualitative and quantitative status of groundwater resources. In order to simulate physical processes of importance for groundwater quantitative and qualitative assessment, a three-dimensional groundwater flow model for the Upper Danube catchment has been developed. Within integrated DANUBIA system, this groundwater model is fully coupled with other hydrological models ("Atmosphere", "Land surface" and "River network"), exchange parameters with them (water fluxes, groundwater level, nitrogen concentration, extraction rates etc.) and simulate quantitative and qualitative processes of importance within the water cycle. The groundwater model itself is of course not 'capable' of fulfilling the role of a management tool; it provides the basic parameters such as groundwater levels and fluxes but is not useful in describing technical, infrastructural, social and political aspects of groundwater management. These aspects are within GLOWA-Danube concept described by socio-economic sub-models, or so called "Actors". Here, an 'Actor' stands for any entity (or object) capable of decision making. In DANUBIA, principal Actors are the main water consumers: households, farmers, industry (entrepreneurs) and tourists. Since water supply companies and communities are also capable of decision making - and are very important stakeholders in the management of water resources - they are also modelled as Actors. Actor's ability to imitate the behaviour of the water users (based on the predefined preferences) and to change their behaviour (based on the predefined rules) makes them able to simulate economic, social and political components of water resources management. Of course this ability is limited only to the extent of predefined behaviour (through so called actions) and possible change of the behaviour (through preference, plans and rules for selection among possible plans). In order to provide for the variability of the behaviour within one actor model (e.g. water supply, household, agriculture, industry, etc.) each principal actors is split into several sub-types. Theses sub-types can have individual preferences, plans and actions that provide them to react differently to changes of the outside conditions (e.g. small water supply company with access to only one groundwater resource would react differently to the decrease in groundwater recharge than the large water supply companies that may have access to various water sources). Some further details on actors modelling in DANUBIA are provided by Janisch et al., (2006).

The structure of the Groundwater management with the “Groundwater” and “Water Supply” model as its central part and the interacting natural and socio-economic models is presented on the Figure 4. Such structure should provide integration of the physical process modelled by hydrologic sub-models) with the socio-economic process (modelled by Actors) through tight coupling of groundwater and water supply components.

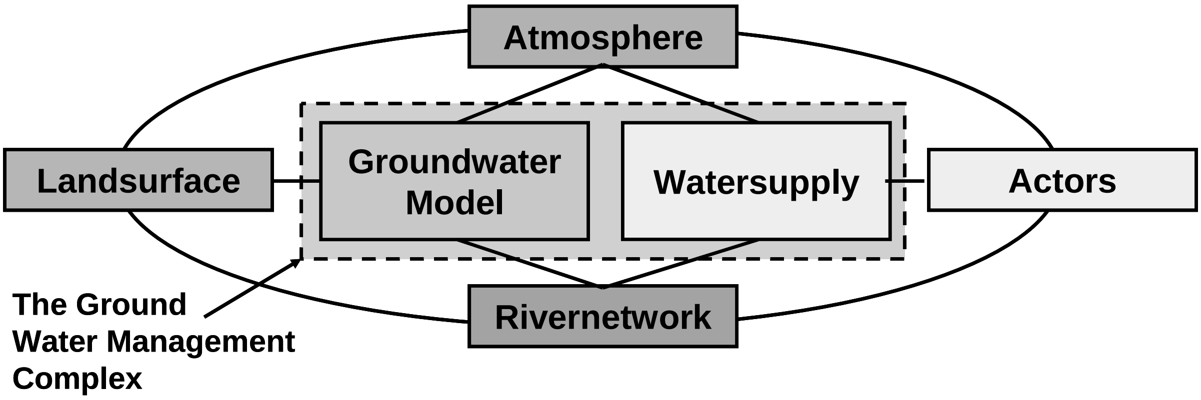


Fig. 4: The groundwater management models and their relations to the main DANUBIA components.

The DANUBIA object GroundwaterFlow was implemented in JAVA and wrapped around the original MODFLOW Fortran code (McDonald and Harbaugh, 1988). Interfaces exist mainly to the Actors component (withdrawal, quality), the RiverNetwork component (exchange with surface water bodies, river stages) and the Soil object (groundwater recharge, groundwater level). The object-oriented DANUBIA model WaterSupply, a member of the Actor package, is a proprietary development and was implemented entirely in JAVA. WaterSupply is in essence an interface and interpreter between the natural science models determining water supply on the one side and the socioeconomic, behaviour-driven Actors models governing demand on the other. Main interfaces in DANUBIA exist to GroundwaterFlow, RiverNetwork and the Actors objects Household, Economy, Farming and Tourism. It is important to mention that rather than aiming to predict the future appearance of water supply in the Danube Basin, such model concept is used to evaluate and compare scenario driven simulations based on rule sets defining the behaviour of the different model components. An extensive description of “Water Supply” model can be found in Barthel et al. (2005 a).

The Groundwater Model

The main aim of the DANUBIA Groundwater component is to assess and predict quantity and quality of the groundwater resources under conditions of Global Change together with the other natural science models. Commonly conceptual hydrological 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 and exchange between different aquifers is required. For example, extraction from wells should lead to a measurable local and regional drawdown in order to be able to assess environmental impacts. 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) was chosen (Barthel, 2005 b).

The hydrogeology of the Upper Danube Catchment is characterized by four major zones: the Alps, the Molasse-Basin, the Jurassic Karst (plus other Mesozoic rocks) and the Crystalline Basement Complex (Figure 5). One main challenge in setting up the conceptual model for the heterogeneous catchment is to find the appropriate number and extent of aquifers needed to describe the main flow characteristics of the basin and to create meaningful model output. In the integrated system the main focus is on the coupled processes close to the land surface, such as groundwater exchange with surface waters, soil, biosphere and atmosphere, and on the exchange with the human part of the water cycle, i.e. water consumption and contamination. This has lead to a conceptual model that focuses rather on the shallow parts of the groundwater system and short to medium term processes (Figure 6). Deep flow systems and long-term processes are neglected due to their minor contribution to the actual water cycle (Barthel, 2005b).

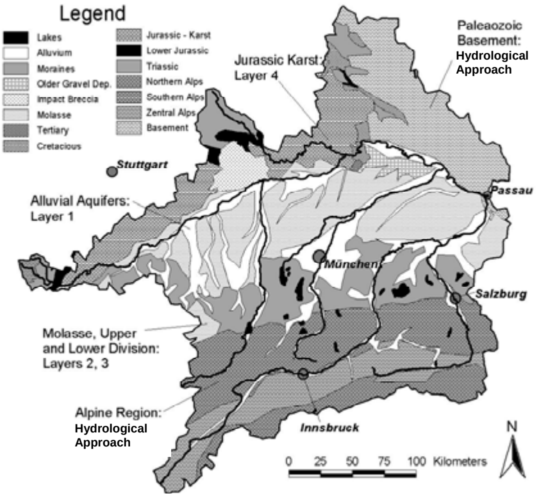


Fig. 5: Schematic geological map of the upper Danube basin.

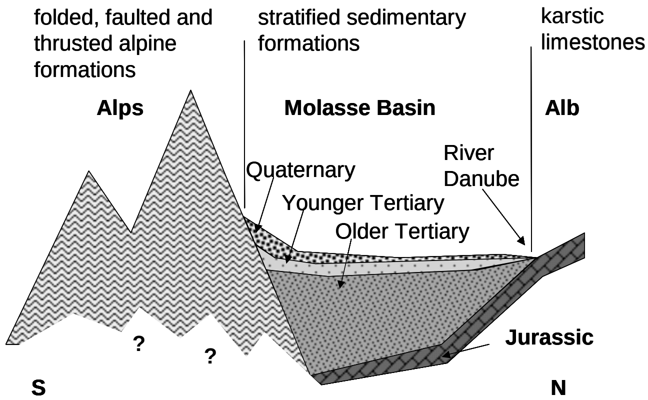


Fig. 6: Schematic geological cross section showing the four model layers.

The Water Supply Model

The organizational structure of water supply in the Danube basin shows a complex, intertwined hierarchy of public water suppliers. Characteristic of water supply within the upper Danube basin is a groundwater-dependent, strongly decentralized, three-tier structure comprising local, community based suppliers (well over 2000), regional special purpose associations (~300) assuming the water supply responsibilities (maintenance, administration, financial matters, and in many cases also technical infrastructure) for a group of communities, and a few supra-regional, long-distance suppliers (~5) supplying regions with few or no resources (Emmert, 1999). Although the use of local resources is generally preferred, many communities draw upon supply from all three organizational forms for security purposes. A number of group suppliers and in particular the long-distance suppliers import or export appreciable amounts of water across the boundaries of the Danube basin, which need to be accounted for in the water balance. This complex structures of water supply in the model area, is to a very large degree reproduced within the model (Figure 7.)

On the other hand with the DANUBIA system, the "Water Supply" model forms the link between various physical models determining water quality and availability and several socio-economic models determining water usage and consumption (Figure 8.). In addition to this integration, the application of "Actor" concept should provide a basis for the creation of an integrated tool for Groundwater Resources and Supply Management. According to this concept the "Water Supply" model objects (i.e. Water Supply Companies) select specific plans and actions based on analyses of parameters calculated by the Groundwater, Rivernetwork and Landsurface components. Furthermore, through a comparison of supply and demand based upon the actual organization of water extraction and distribution within the upper Danube catchment, WaterSupply provide information about the state of the resources, such as water availability, quality and price to the other Actors. These then influence the behaviour of the Actors (selection of their plans and actions) and close the water management circle. By such modelling concept it is not meant to simulate the exact behaviour of the water users of the future appearance of the water supply infrastructure but instead, based on the water resource management plans and actions to identify areas which may suffer water stress (Barthel et al., 2005 a)

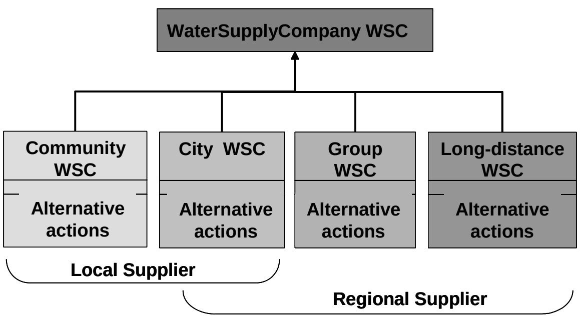


Fig. 7: Organizational structure of Water Supply in Upper Danube

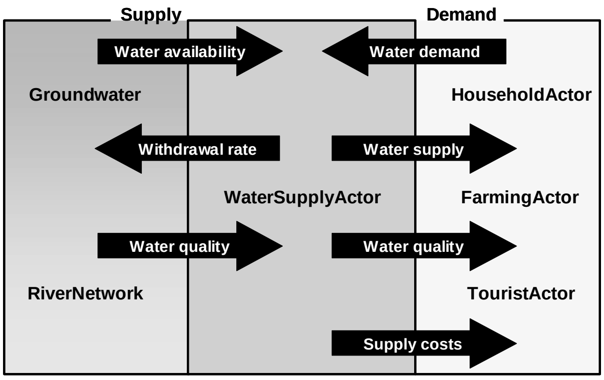


Fig. 8: Water supply: as the interface between supply and demand

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. More detailed result descriptions for DANUBIA as a whole can be found in Strasser et al. (2005). In the following, only disciplinary results related to groundwater management will be presented.

For a previously described DANUBIA Groundwater model the calculated piezometric heads are generally acceptable when compared to measured mean values (overall $R^2 = 0.97$ for steady state results, Figure 9) and time series (Figure 10). However, big differences exist in various parts of the basin and for various aquifer sections. Generally, the deviations from the natural situation are small for the unconsolidated, quaternary aquifers that fill river valleys and gravel plains but large for the Jurassic Karst, the Alps, the crystalline regions and parts of the Tertiary. Since the Quaternary aquifer is the most important for the short to medium term (days to several years) exchange of the groundwater with surface water bodies and the atmosphere, this is in many cases acceptable. Furthermore, since the decision support system DANUBIA aims at integrated management on the regional scale it is important to address the issues of importance at this scale. The inconsistencies that the model shows for small local aquifers are often of no importance for the regional water management and can be addressed with more detailed - and more problem specific - models.

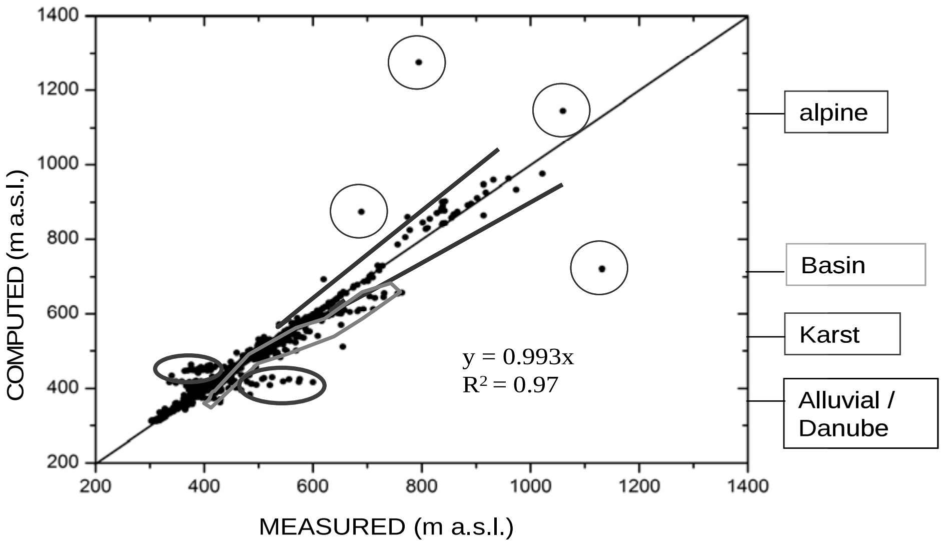


Figure 9: Comparison of measured and calculated values of groundwater heads for a steady state simulation.

A comparison of the groundwater model results calculated for a reference period (1995-99) and a wet (95, 96 + three times 2002) and a dry scenario (95, 96 + three times 2003) shows that the model reacts in a reasonable way to the main input parameters, namely the groundwater recharge calculated by the DANUBIA soil model. This is the case for single model cells (Figure 10) as well as for the whole catchment (Figure 11). In both cases a significant decrease of the groundwater level results from the lower groundwater recharge (30% less) originating from the much dryer climatic conditions in the exceptionally hot and dry year 2003. Figure 10 reveals a limitation of the large scale model, namely the smoothing effect of the relatively large grid size of 1 * 1 km. Depending on the nature of problems the model will be used to solve, this has to be accounted for.

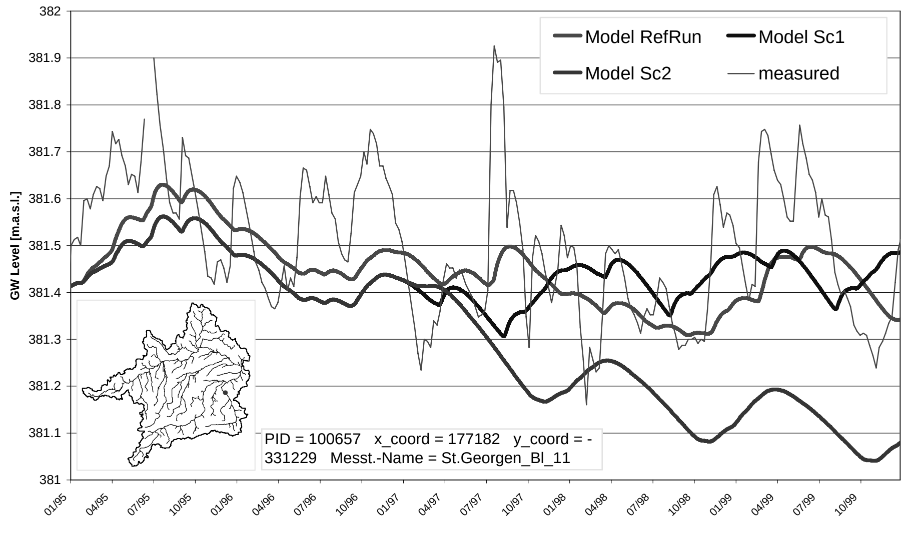


Fig. 10: Comparison of measured and calculated groundwater levels for an observation well near the river Salzach (Bavarian/Austrian border). RefRun: Validation period 1995-1999, Sc1: "wet" scenario, 1995,1996, 3x2002, Sc2: "dry" scenario, 1995, 1996, 3x2003.

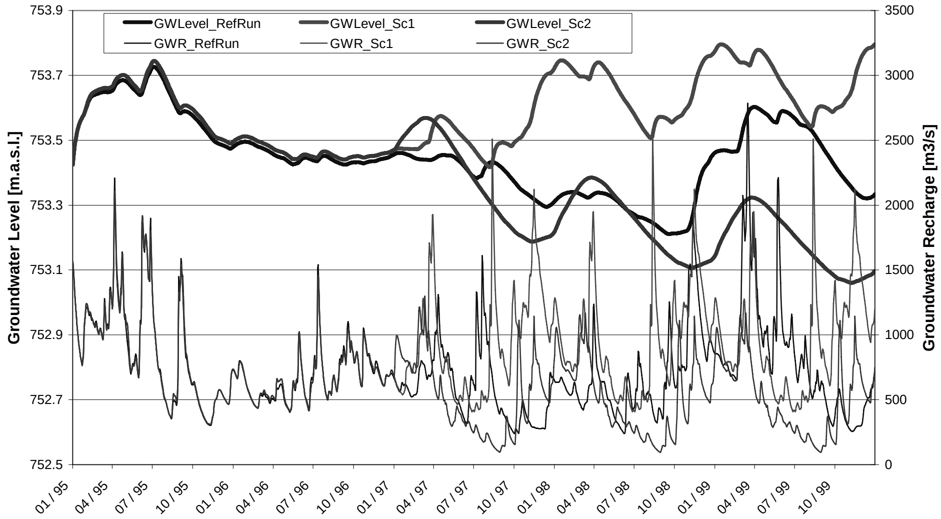


Fig. 11: Comparison of the mean groundwater level and the mean groundwater recharge for the whole catchment for the reference period (RefRun), the wet (Sc1) and the dry scenario (Sc2).

The scenario results for the DANUBIA WaterSupply model are, as for all actors models, less significant due to the relatively short simulation period of five years. However, it can been seen in Figure 12 that the domestic drinking water demand increases noticeably during the hot and dry summer in 2003. This, in turn, resulted in a slightly higher total groundwater withdrawal, which, however, was negligible looking at the overall water balance of the groundwater flow component. In addition, the decrease in groundwater recharge plus the increase in water demand did not yet invoke a limitation in drinking water supply. Since such extreme conditions were not known in the Upper Danube catchment in the past, it is difficult to decide how to set the thresholds. This will in future be discussed with different stakeholders.

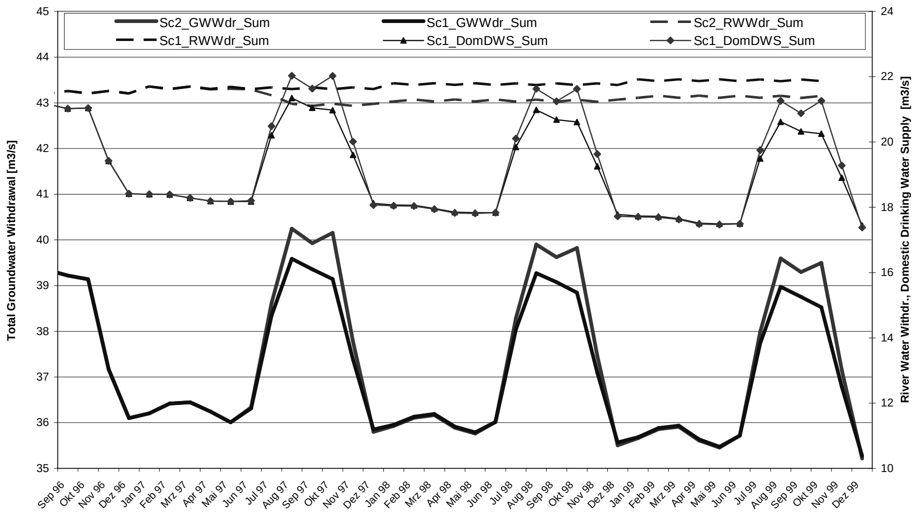


Fig. 12: Comparison of domestic drinking water supply, groundwater and river water withdrawal for the whole catchment for the wet (Sc1) and the dry scenario (Sc2).

In order to understand the WaterSupply model results, it is important to remember that the main role of WaterSupply is to act as a link between the demand and the resources side of the systems. Being a linking part in an integrated system, the 'results' are highly dependent on the results of the connected models. A 'good result' of WaterSupply is achieved if all the demands can be satisfied following the predetermined patterns of water distribution patterns in the real world. From the decision makers point of view, interesting results are only to be expected in cases where the present day situation, which is characterized by an almost 100% satisfaction of demands is disturbed, e.g. by extreme climatic conditions. Only then will the 'business as usual' mode of behaviour be left. Such deviations can then be interpreted.

In Figure 13 the difference between the DomesticDrinkingWaterDemand calculated by the Household Model and the DomesticDrinkingWaterSupply calculated by the WaterSupply Model is shown for a winter and a summer situation in 1999. The results originate from a simulation used for model validation for the years 1995 to 2000. All models were previously tested and adjusted for the years 1995 and 1995. Since the input values were slightly different in 1999 from the 95/96 values that the model was adjusted to, a deficit for a small number communities was calculated (15 in winter, 45 communities in the summer). However, no water scarcity is known for 1999. On the other hand, the deficits are very small and the percentage of undersupplied communities is less than 1% or 2 % for the winter and summer respectively. Nevertheless a deficit in 1999 has to be considered an error. To find the cause of this error is a difficult task in the integrated system because it might not even be an error in the WaterSupply model (its data base or algorithms) but also an error in the partner models, e.g. the Atmosphere model that calculates the precipitation which is used to calculate the groundwater recharge in the soil model and so forth.

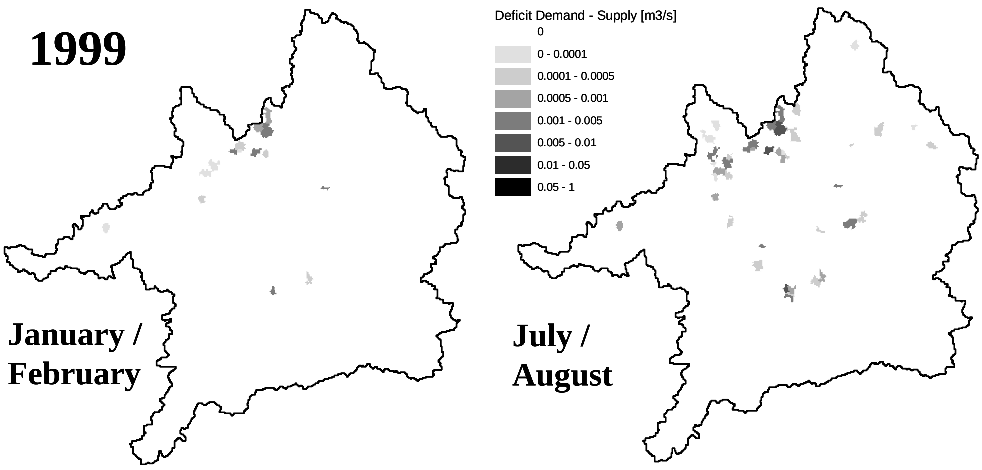


Figure 13: Deficits in Water Supply caused by the deviation in the initial conditions for the reference run (1995-2000) and the validation period (95/96) in January (left) and July (right) of 1999.

Conclusions

The project GLOWA-Danube is a highly integrative scientific project. Within the first working period (2001-2004) it has been shown that a web-based model integrating natural as well as socioeconomic sciences can be developed using an object oriented approach. As far as the large scale groundwater modelling is concerned it can be said that despite the difficulties groundwater models of this size and heterogeneity can be applied successfully if two main aspects are considered carefully: a) setting of the appropriate conceptual model, namely in the adequate definition of the model layers geometry and boundary conditions, and b) careful use of such models, especially as a part of IWRM system, only to address long term, regional problems. The development and validation of an object-oriented water supply model for the upper Danube area provided not just the possibility for "rule – based" simulation of technical, economic and social aspects of water supply withdrawal, transport and distribution, but its integration with the hydrologic, on one side, and socio-economic, on another side, represents the basis for the simulation of integrated groundwater management scenarios.

In the future of GLOWA-Danube, the focus will be even more towards the active integration of the stakeholders from the field of water resources management. Decision-making 'rules' will be debated with the relevant stakeholders and adapted where necessary. Based on these rules, the object-oriented "Actor" model Water Supply will be transformed to a "deepActor" model with limited decision-making functionality, with WSC actors able to respond to their environment and behave in a goal-oriented manner to bring about change in the water supply system in response to changing conditions with regard to the climate, water availability and quality, political and social boundary conditions, and changing demand. The second project phase will furthermore be dedicated to the refinement of the various GLOWA-Danube models and to the formulation, testing and comparison of complex scenarios of future development with the aim of identifying sustainable forms of water management and consumer behaviour. Ultimately, DANUBIA will be able to serve as a tool for monitoring, analysing and modelling the impacts of Global Change on nature and society in the Upper Danube basin for various future scenarios, taking into account a multitude of environmental, social and economic aspects formulated by the water-related stakeholders.

Acknowledgement

The authors wish to thank the German Ministry for Education and Research, the Bavarian State Ministry for Science, Research and Fine Arts, the Baden-Württemberg Ministry of Science, Research and the Arts and the Universities of Munich and Stuttgart for funding GLOWA-Danube. Furthermore we like to thank all partners in GLOWA-Danube for their support.

References

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

Barthel R, Nickel D, Meleg A, Trifkovic A, Braun J (2005 a) Linking the physical and the socioeconomic compartments of an integrated water and land use management model on a river basin scale using an object-oriented water supply model. - Physics and Chemistry of the Earth.

Barthel, R., Rojanschi, V., Wolf, J. und J. Braun (2005 b) Large-Scale Water Resources Management within the Framework of GLOWA-Danube - Part A: The Groundwater Model. - Physics and Chemistry of the Earth.

BMBF (German Ministry of Research and Education, 2002) German Programme on Global Change in the Hydrological Cycle Status Report 2002 (Phase I, 2000 - 2003) (http://www.glowa-danube.de/PDF/reports/statusreport_phase1.pdf).

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

Emmert M (1999) Die Wasserversorgung im deutschen Einzugsgebiet der Donau. Wasserwirtschaft 89, 7-8, 396-403.

Janisch S., Barthel R., Schulz, C., Trifkovic, A., Schwarz, N., Nickel, D. (2006) A Framework for the Simulation of Human Response to Global Change - Geophysical Research Abstracts, Vol. 8, 06195, 2006

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, pp 621-634.

Mauser, W., & Ludwig, R. (2002): GLOWA-DANUBE – A research concept to develop integrative techniques, scenarios and strategies regarding the global change of the water cycle. In: Beniston, M. (Ed.): Climatic Change: Implications for the hydrological cycle and for water manage-ment. Advances in Global Change Research, No.10, Kluwer Academic Publisher, Dordrecht, Boston, 171-188.

Mauser W, Barthel R (2004) Integrative Hydrologic Modelling Techniques for Sustainable Water Management Regarding Global Environmental Change in the Upper Danube River Basin. - In: Research Basins and Hydrological Planning (Ed., Xi, R.-Z., Gu, W.-Z., Seiler, K.-P.), .), pp. 53-61

McDonald MG, Harbaugh AW (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.

Strasser U, Mauser W, Ludwig R, Schneider K, Lenz V, Barthel R, Sax M (2005) GLOWA-Danube: Integrative Global Change Scenario Simulations for the Upper Danube Catchment – First Results. In: Papers of the International Conference on Headwater Control VI: Hydrology, Ecology and Water Resources in Headwaters. IAHS, Bergen, Norway.

Tenhunen JD, Kabat P (Ed.) (1999) *Integrating Hydrology, Ecosystem Dynamics, and Biogeochemistry in Complex Landscapes*, John Wiley & Sons, Chichester, 1999