GLOWA-Danube: Integrative Global Change Scenario Simulations for the Upper Danube Catchment – First Results

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1. Introduction

The objective of GLOWA-Danube is to investigate and explore new integrative techniques and methods, leading to a decision support system for water resource management in the Upper Danube catchment area. The project partners from Germany and Austria build a broad scientific basis from natural sciences (meteorology, hydrology, hydro-geology, plant ecology, glaciology, remote sensing, computer science) and socio-economic disciplines (agricultural and environmental economy, environmental psychology and tourism research). In the first project phase (2001 - 2003), research was focussed on the development for a prototype of a web-based Global Change Decision Support System called DANUBIA (Mauser & Ludwig 2002, Ludwig et al. 2003, Mauser 2003). This tool for integrative environmental monitoring is based on existing data of the study region and on existing disciplinary models for the description of the various water related processes. The DANUBIA system will be able to produce scenarios of future global change and provide support to decision makers by clarifying the impacts of different potential water resources management strategies. With the help of such a system, it will be possible to develop and analyse scenarios from natural and social science perspectives. Potential stakeholders of the GLOWA-Danube project are, among others, the administrative authorities on the regional level of the countries involved, water supply companies, farmers and the farming industry, the hydropower industry, tourism organisations on the regional and local level, insurance companies as well as NGO's like the International Commission for the Protection of the Danube River, national park authorities, the World Wildlife Fund WWF or the German environmental protection organisation BUND.

The Upper Danube catchment is located in Southern Germany and Western Austria, with smaller parts in Switzerland, the Czech Republic and Italy. It comprises about 77,000 km², 8.2 Mio. inhabitants and an altitude difference of more than 3,500 m from the summits of the Alps to the Danube lowlands. Whilst in the southern parts it is a true Alpine catchment, the central region consists of flat to undulating mountain foreland terrain. Human activities range from extensive agriculture in the Alps to agro-industry in the forelands, from scattered dwellings in remote valleys to large cities like Munich, from small family-run businesses to high tech industry. Due to these strong gradients in almost all natural and socioeconomic factors the chosen study region is highly sensitive to the consequences of a future global change. Already existing water use conflicts between agriculture, industry, tourism and a changing population structure may increase severely in the future.

In this paper, first results of a reference run of the system for validation purposes as well first test scenarios – consisting of a synthetically provided but physically consistent cold/wet and respective warm/dry periods – are presented.

2. Integration Techniques

A valid integration of all disciplines involved in GLOWA-Danube is crucial for the creation of a successful decision support system DANUBIA. Each single discipline within the project can rely on a long experience and well established models in their own domain. These disciplinary models are generally highly sophisticated and specialised in their model core, in order to account for the needs of disciplinary research. Competences outside of the model core, however, are usually less developed, and often boundary conditions are kept constant or are described in a simplified way. Such models are not prepared for coupling with other disciplines and hence only have a limited capability in dealing with complex questions and integrated scenarios. Within GLOWA-Danube integrative techniques have been developed and applied in order to overcome the mentioned deficiencies and to exploit the existing disciplinary expertise for an integrative research of the water cycle (Mauser & Ludwig 2002).

A proxel is the basic spatial unit for all processes described in the DANUBIA system. "Proxel" stands for process pixel. It enables the coupling of models on a common spatial platform and to exchange variables with a well defined spatial representation. The agreement of all project partners including the socioeconomic disciplines to such a raster based modelling approach allows a direct coupling of natural to socioeconomic models on the same spatial basis. A key to the approval of the proxel concept in the socioeconomic sciences is the commitment to agent based modelling. In this approach, human activities are spatially resolved and represented by describing multiple actors with varying preferences and a distinct behaviour and decision making.

A second key element of the DANUBIA concept is the object orientation of the model. Each sub-model is regarded as an independent object with certain, well defined public functionalities and a private modelling core. All other partners can profit from this expertise by using the offered public methods and parameters. Additionally, the well established advantages of object oriented modelling like inheritance and simple reuse of existing implementations contribute to a successful application within DANUBIA. Finally, object orientation simplifies the model to be run over the world wide web in several locations at the same time with well established RMI techniques.

In modern computer science and software engineering, the Unified Modelling Language UML has been established as a quasi standard for large projects with heterogeneous partners (Booch et al. 1999). In the GLOWA-Danube project, UML has been used for the design of the model framework of the DANUBIA system as well as for the definition of all interfaces between the model components (Figure 1). The UML serves as a common language between the disciplines, and helps in explaining the disciplinary models as well as in defining unique core objects and interfaces between those objects. With the common commitment to designed interfaces, a clear and unambiguous basis for the exchange of parameters and variables between the core models has been established.

Besides these aspects of technical integration, the scientifically sound coupling of the former disciplinary models requires multilateral discussions and negotiations of the contributing disciplines. The delineation of core competences allows a consistent description of all physical and socioeconomic processes that have to be modelled exactly once within the DANUBIA system. Sophisticated algorithms of each modelled process are implemented by the most competent group. At the same time, each group can rely on the expertise of the other groups in areas where it does not feel competent. Consequently, the entire project is profiting most from each single discipline's expertise, while avoiding unnecessary simplifications or even redundant modelling of the same processes.

3. Stakeholder dialog and Decision Support

Now, after entering into the second project phase (2004 – 2006), potential stakeholders will be invited and introduced to the project at a stakeholders conference in the coming months; their actual participation is a self-nominative process. Common interest groups will be formed that define scenarios to be run with DANUBIA. A scenario is defined as a set of existing natural, legal and socioeconomic boundary conditions as well as explicit decisions of stakeholders regarding the action to be taken in the future that are translated into variable starting conditions of the scenario. The mediation process will take place on both the stakeholders' and the modellers' sides, in order to abstract from particular perspectives and interests and to facilitate constructive communication.

As a starting point, the modellers' group will produce – besides model runs in the past for validation purposes - a zero or "business-as-usual" scenario from the present to the close future. It can reveal sensitivities of single parameters and quantify feedback mechanisms, and will show the capabilities of the DANUBIA system implemented so far in order to raise realistic expectations in the stakeholders' groups.

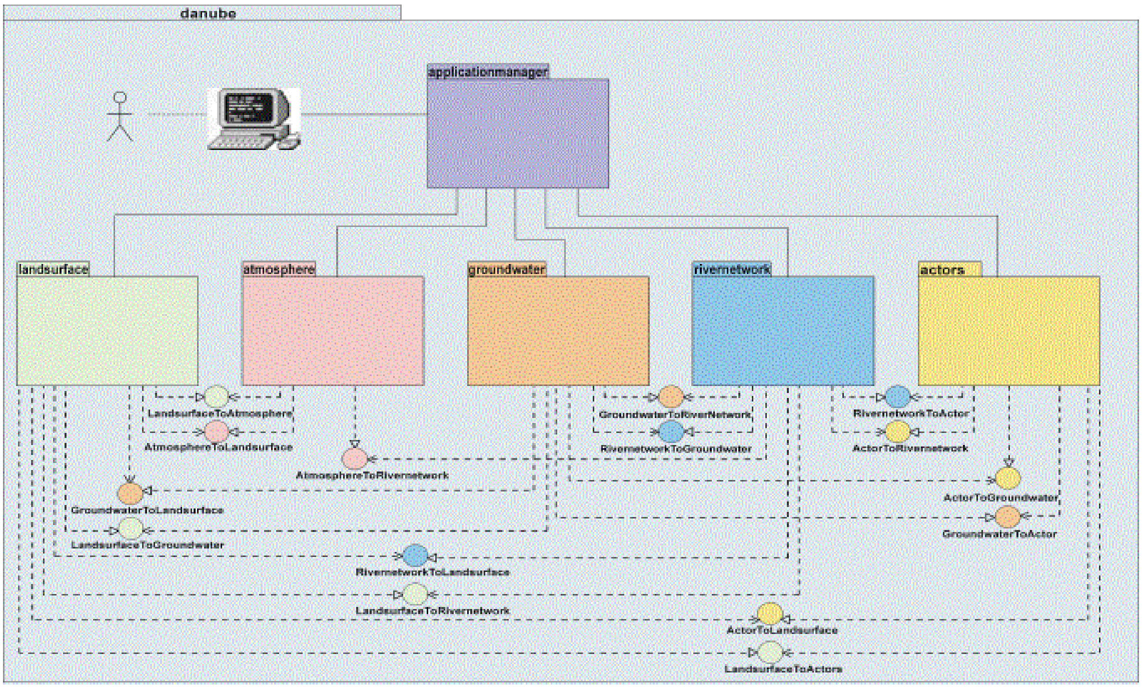

Figure 1: Simplified UML diagram of the DANUBIA system showing the main components and the interfaces that ensure the data exchange.

In a second step, simple scenarios are developed in direct cooperation and mutual agreement with stakeholders, where the actual scenario is delivered by stakeholders' groups, while the modellers have to ensure the model's flexibility and capability to react on the chosen scenario. Likewise, the consequences of different decisions of a stakeholders' group can be observed, clarified and understood. The more specific a single scenario is defined by a stakeholder, the more likely DANUBIA will not be able to incorporate all consequences in its standard mode and hence will have to be adjusted accordingly. Therefore it is crucial that on the one hand stakeholders' interests are respected and accounted for from the very beginning of their involvement by the modellers, while on the other hand the stepwise model and competence building process has to be respected and supported by the stakeholders.

4. Technical state

A first system prototype of DANUBIA has been implemented to prove the feasibility of the approach. It shows that the system is already running, the interfaces and the data exchange between the components are correctly set up and the resulting spatial and temporal pattern of the different calculated parameters are consistent (GSF 2002). There is no claim of correctly calculated results yet, as the system is still under development. However, the system logic proved to be functional and valid.

DANUBIA is currently running on a LINUX-Cluster with a spatial resolution of 1 km². Time management and network communication have been implemented. The time-steps within the different components vary from 15 minutes to once per year.

Examples of first results are sown in figure 2. The various objects of DANUBIA use a central database for common tasks, as well as local databases for data and tasks which are relevant only for one discipline. Within these modelling objects a variety of parameters are calculated of which only those needed by other models are exchanged through the interfaces.

DANUBIA is not limited to the current spatial context. The framework design allows fast and simple changes to different subcatchments, periods or spatial resolutions, scale independent algorithms and available data provided. Studies on scaling are currently under way (Mauser et al. 2004).

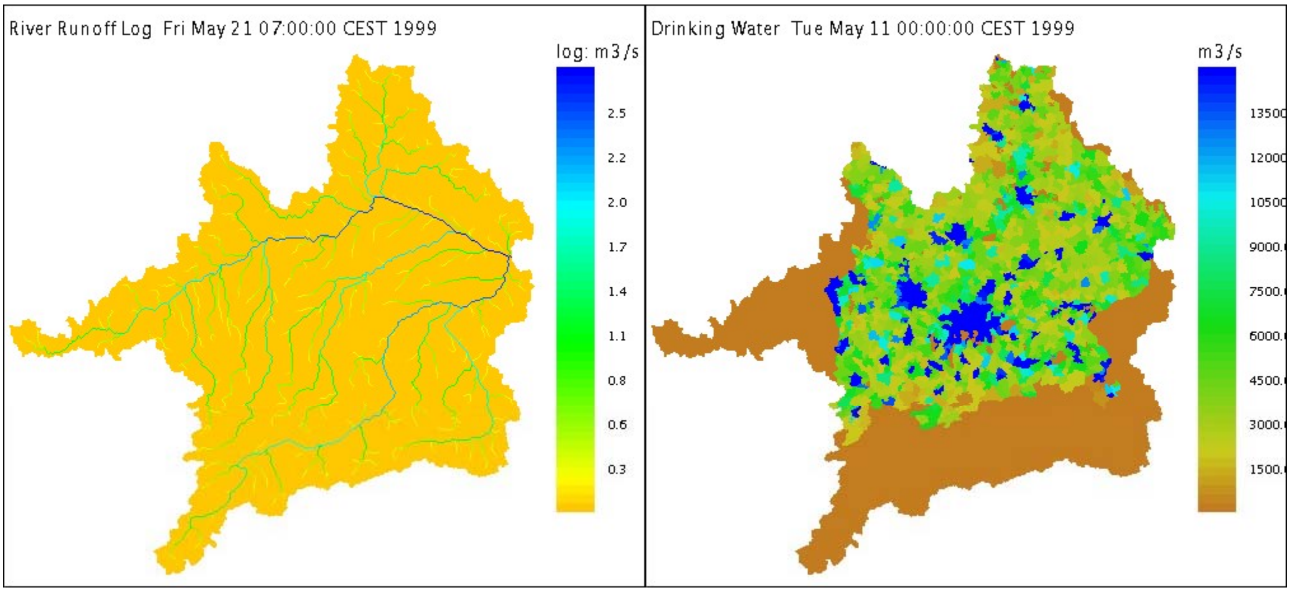

Figure 2: Graphical representation of parameters river runoff and the drinking water demand as modelled by the DANUBIA prototype. Drinking water (right) has only been modelled for the Bavarian sector of the catchment.

After the validation of the system, a first set of scenarios has been defined: as a reference, the period from 1. Jan. 1995 to 31. Dec. 1996 has been chosen. With this reference two scenario runs can be compared: one is synthetically provided by stacking three times the climatic forces of 2002 (a comparably cold and wet year), and the ones of 2003 (a comparably warm and dry year), respectively. This set of scenarios was formulated to give a first impression of the sensitivity of the system to changing (but physically still consistent) climatic inputs.

4. First results - examples

4.1 Biomass production

Agricultural biomass production and land use change are of key importance in global change research. Since the major portion of the precipitation is used for evapotranspiration, the water demand by vegetation is a key to analyze future water availability. Vegetation water demand is not only governed by environmental processes, but also strongly dependant upon socioeconomic processes, particularly agriculture: worldwide, agriculture is by far the most important water user (FAO, 2003). Climate change will bring about changing vegetation water demand as well as changes in biomass production and land use.

Thus, investigating the effects of climate change upon future water availability requires a process based description of all relevant environmental processes, particularly with regards to plant development, vegetation growth and water use as well as with respect to modeling of the human impact on land use changes and agricultural water use. To ensure the applicability of the system for global change research all modeled processes must be based upon a proper understanding and description of the relevant processes rather than on empirical models. Thus vegetation growth in DANUBIA is calculated using process based photosynthesis, respiration and transpiration models (Baldocchi 1994, Ball et al. 1987 and Farquahar & von Caemmerer 1982) to describe gas fluxes of CO_2 and H_2O. Plant specific phenological development and allocation tables result in a dynamic plant growth, which responds to temporal and spatial variations of meteorological drivers, soil properties and agricultural management practices. All fluxes are calculated with an hourly time step. Figure 3 shows transpiration and gross primary production (GPP) for a period of one week for a barley field for 1997. While the stomata conductance governs both CO_2 and H_2O fluxes, the transpiration flux is a strong function of the saturation deficit of the atmosphere and the CO_2 flux depends strongly upon the CO_2 gradient between leaf and atmosphere. Although the figure clearly shows the close coupling of both fluxes, they are however not always proportional.

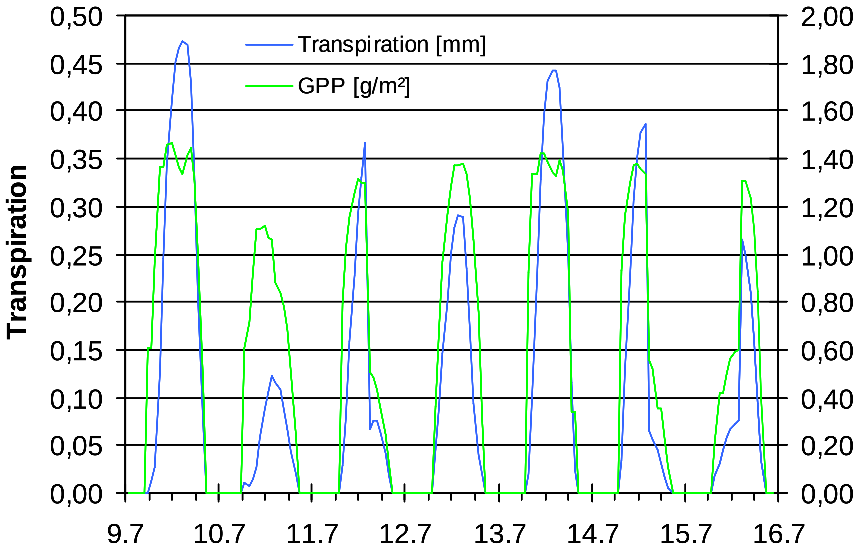

Figure 3: Transpiration and gross primary production for a barley field, 9.-17. Jul. 1997, Wilzhofen.

Figure 4 shows the comparison of the modeled and measured biomass and LAI for the same barley field. While during the growth period LAI and biomass match quite well, the senescence of the LAI is not accurately modeled yet. To investigate the responsiveness of DANUBIA to different climate conditions model runs were performed for 1995, 2002 and 2003.

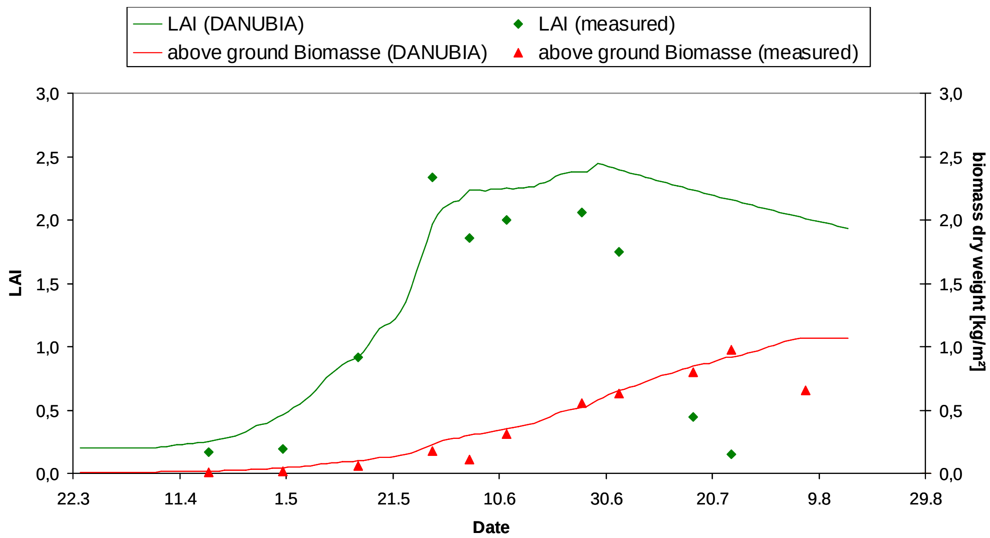

Figure 4: Comparison of modeled and measured plant parameters for summer barley, Wilzhofen 1997.

While 1995 served as a reference for a normal year, 2002 and 2003 were selected as examples for cold/wet and warm/dry years respectively. The resulting change in biomass production as compared to 1995 is shown in figure 5. For large parts of the predominantely agriculturally used lower Danube area, 2003 resulted in a significant decrease of the produced biomass. The modeled trend in the overall biomass production for 2002 and 2003 matched data from the agricultural statistics quite well. DANUBIA diagnoses a strong decrease in biomass production for wheat (-15%) in 2003 and a slight increase for barley (4%) and corn (7%). The agricultural statistics indicated a slight decrease for wheat (-4%), a strong increase for barley (+16%) and a slight increase for corn (5%). Currently improvements of the model parameterization as well as development of additional model components to account for nitrogen and water stress as well as agricultural management etc. are developed. It is expected that these improvements will lead to a further increase in responsiveness of the model and to improved comparisons with field measurements and statistics. The modeled biomass yield as well as the status of the crop development is provided within DANUBIA to the farming decider. This DANUBIA object decides on land use changes as well as management alternatives based upon economic considerations. Changes in biomass production as indicated in the previous figure significantly affect land use and agricultural management decisions which in turn affect agricultural water demand and water use.

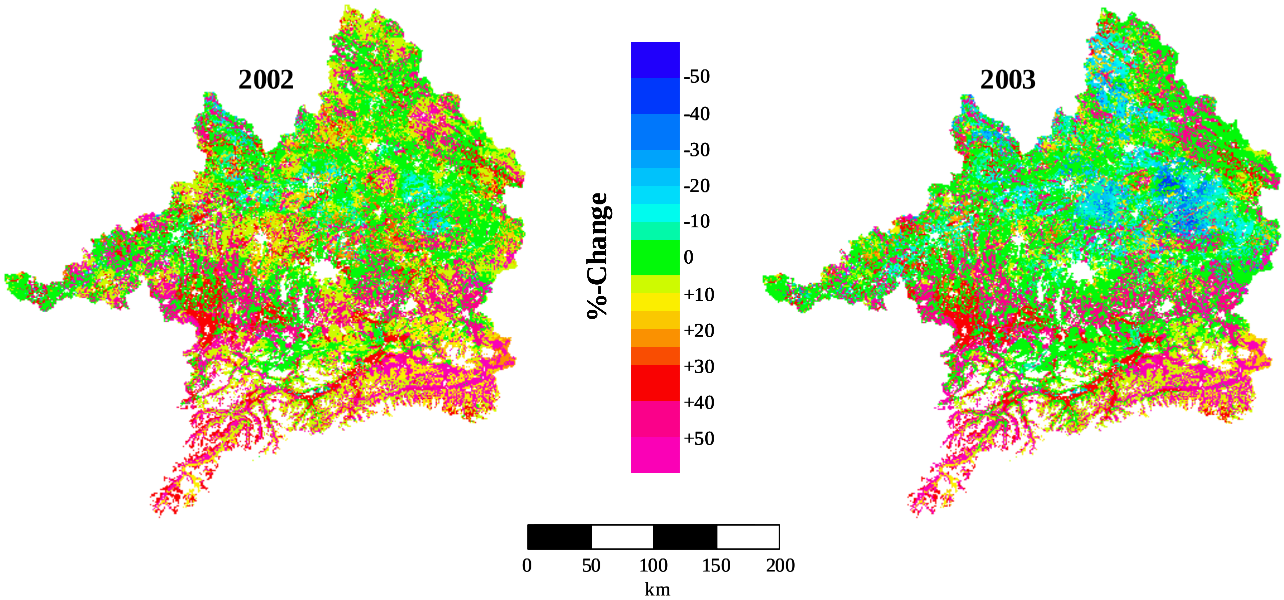

Figure 5: Modelled change in biomass production (2002 and 2003, respectively) as compared to 1995.

4.2 Groundwater

According to worldwide or European standards such as the European Water Framework Directive, groundwater management has two main objectives: to provide water in sufficient quantity and quality to different consumers and at the same time to maintain and guarantee a good qualitative and quantitative status of groundwater resources. Whereas a good quality can be described relatively simple by evaluating the chemical composition of groundwater, a good quantitative status is far more difficult to define because of the varying nature of groundwater resources of different types in different climates. Since groundwater is the major drinking water resource in Southern Germany, the groundwater system and its accurate representation play a major role in the integrated model DANUBIA. Within GLOWA-Danube, a model for three-dimensional groundwater flow has been developed, based on the original MODFLOW code (McDonald & Harbaugh, 1988). The numerical groundwater flow model was developed on the basis of a conceptual hydrogeological model of four layers. This groundwater model is of course not 'capable' of carrying out any management tasks - management is done by people - but in case of integrated models designed to simulate future scenarios this management needs to be partly represented within the integrated model itself. In DANUBIA, the groundwater model provides input for the DANUBIA WaterSupply object. Interfaces mainly exist 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 WaterSupply model 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. Through a comparison of supply and demand based upon the current organization of water extraction and distribution within the upper Danube catchment, the WaterSupply model aims to identify areas which may suffer water stress (Barthel et al., 2005).

The piezometric heads calculated by the DANUBIA groundwater component are generally acceptable when compared to measured mean values (overall R^2 = 0.97 for steady state results, figure 6) and time series (figure 7). However, big differences exist in various parts of the basin as well as for various aquifer sections.

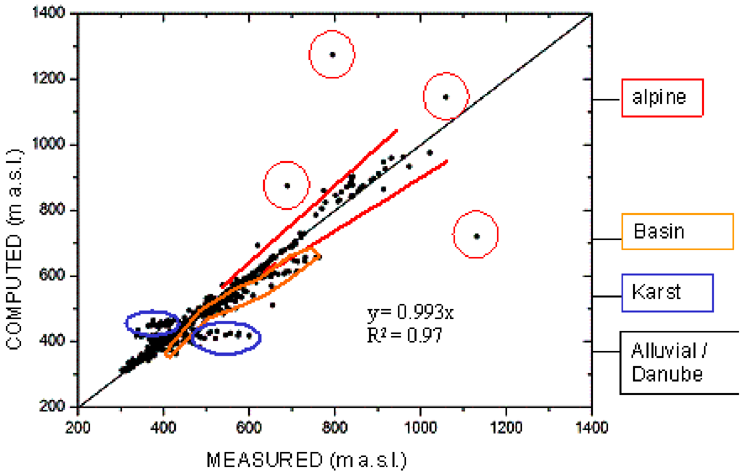

Figure 6: Comparison of measured and calculated values of groundwater heads for a steady state simulation.

Generally, the deviations from the natural situation are small for the unconsolidated, quaternary aquifers that fill river valleys and gravel plains (layer 1) but large for the jurassic Karst, the Alps, the crystalline regions and parts of the Tertiary (figure 6). 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 still in many cases acceptable.

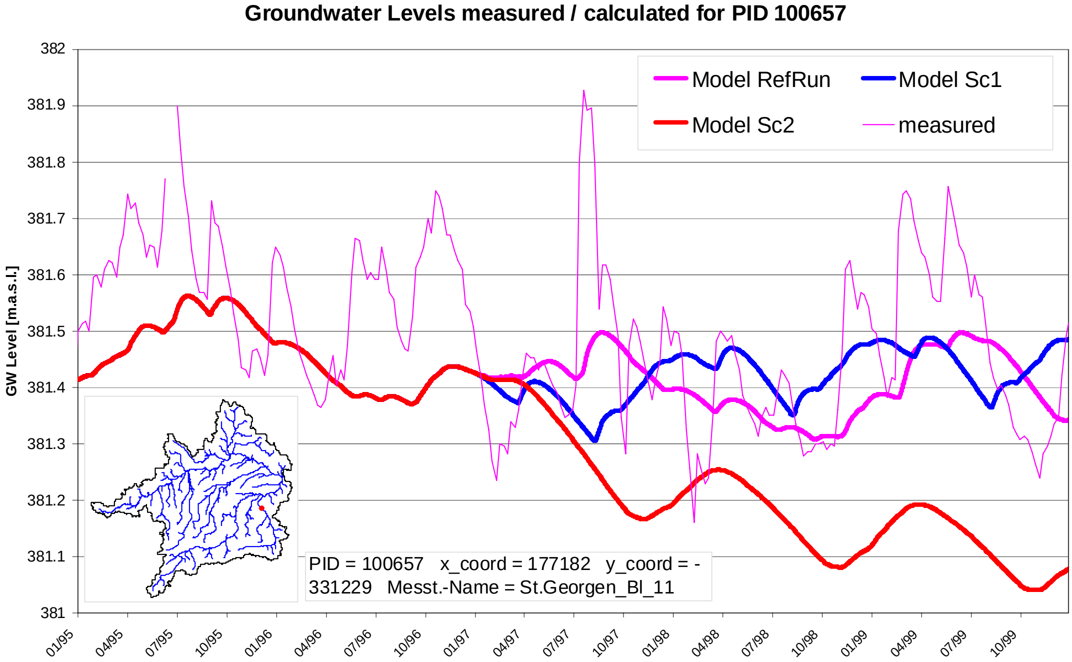

Figure 7: Comparison of measured and calculated groundwater levels for an observation well located near the river Salzach close to the Bavarian / Austrian border. RefRun: Model validation period 1995-1999, Sc1: “wet” scenario, 1995-1996, 2002, 2002, 2002; Sc2: “dry” scenario, 1995, 1996, 2003, 2003, 2003.

A comparison of the model results calculated for the reference period 1995-99 and a wet scenario (95, 96 and three times 2002) and a dry scenario (95, 96 and 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 object. This is the case for single model cells as well as for the whole catchment. In both cases a significant decrease of the groundwater level results from the lower groundwater recharge (30% less during the dry scenario) originating from the much dryer climatic conditions in the exceptionally hot and dry year 2003. Figure 7 reveals a limitation of the large scale model, namely the smoothing effect of the relatively large grid size of 1 km^2. Depending on the nature of problems the model will be used to solve, this has to be accounted for.

Currently, great efforts are being made to further merge the Groundwater and the WaterSupply model in order to fulfil the task of creating an integrated tool for groundwater resources and supply management. This is especially important for the deep actor framework which is in development.

4.3 Water management

At the end of the first project phase of GLOWA-Danube a first validation run was conducted for the water balance related system components from 1. Jan. 1995 to 31. Dec. 1996. Choosing this period ensures that an entire hydrological year is represented and enough modeling time for storage sensitive processes is allocated, e.g. for the snow or the soil water components. With this first integrative model run the single model components could be validated, and the coupling of these components in DANUBIA could be tested. The system provides point output, spatially distributed results as well as balances for validation issues. As an example, figure 8 shows areal output of the Landsurface component for 22. June 1996 (1:00 p.m.): radiation balance, effective precipitation, soil water balance in the upmost layer, direct runoff, interflow and groundwater recharge.

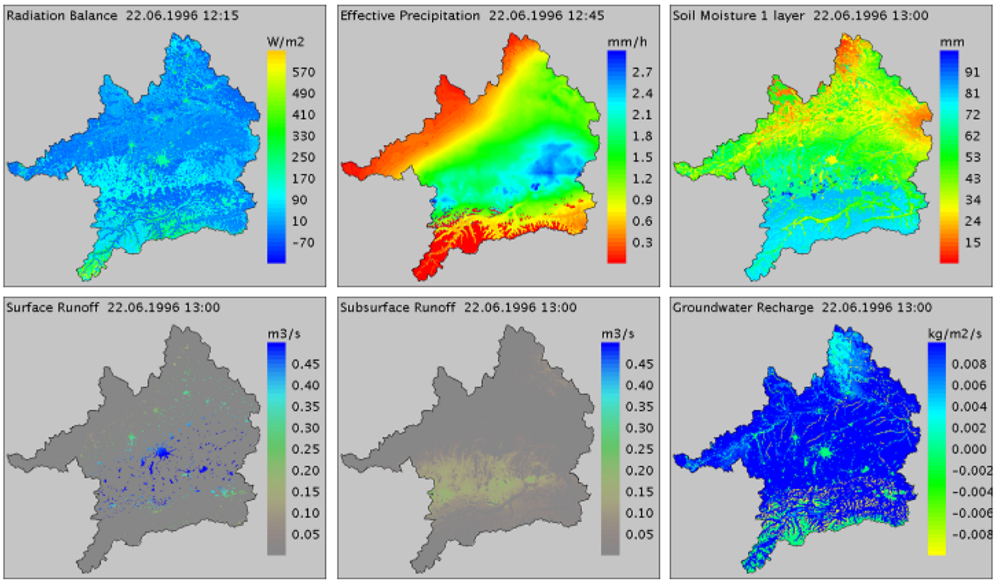

Figure 8: Examples of spatially distributed outputs during runtime of DANUBIA for June 22nd 1996, 1 pm.

Accumulating the water balance terms for the fluxes modeled with the component land surface over the entire area and the period of the hydrological year 1996 results in a very good correspondence with the runoff measured at the catchment outlet (table 1).

Table 1: Simulated water balance of the model component Landsurface for the hydrological year 1996 in comparison to the recorded runoff at gauge Achleiten.

Water balance term 1996	Modelled [mm]	Measured [mm]
Effective precipitation	924	
Evaporation	102	
Transpiration	214	
Change of soil water storage	50	
Direct runoff	116	
Interflow	247	
Groundwater recharge	195	
Total runoff generation	**558**	
Runoff gauge Achleiten		**528** (1278 m^3/s)

The comparison of runoff represents an integrative validation of the modeling system, because all components finally have an effect on the simulated runoff. In particular, the representation of the temporal dynamics can be tested. Figure 9 shows a comparison of the modelled total runoff at the catchment outlet (gauge Achleiten, 76.660 km^2) with the measurements for the entire validation period 1. Jan. 1995 to 31. Dec. 1996. Thus, the modeled runoff overestimates the measurements by about 15 % with the larger deviations during the initialization phase and the winter months, respectively. After volume correction, the modeled runoff correlates closely with the measurements. Rising and recession limbs of the hydrographs are matched quite well, and also the timing of the peak occurrences. The Nash-Sutcliffe efficiency reaches 0.67 after volume correction, which is quite a reasonable value for “unfitted” models. The same observation also accounts for many other gauges in the catchment. It can be concluded that the translation and retention processes are appropriately modelled for the river networks in the catchment. However, for smaller rivers significant high frequency components can be observed in the simulation results, the reasons for which are currently discussed.

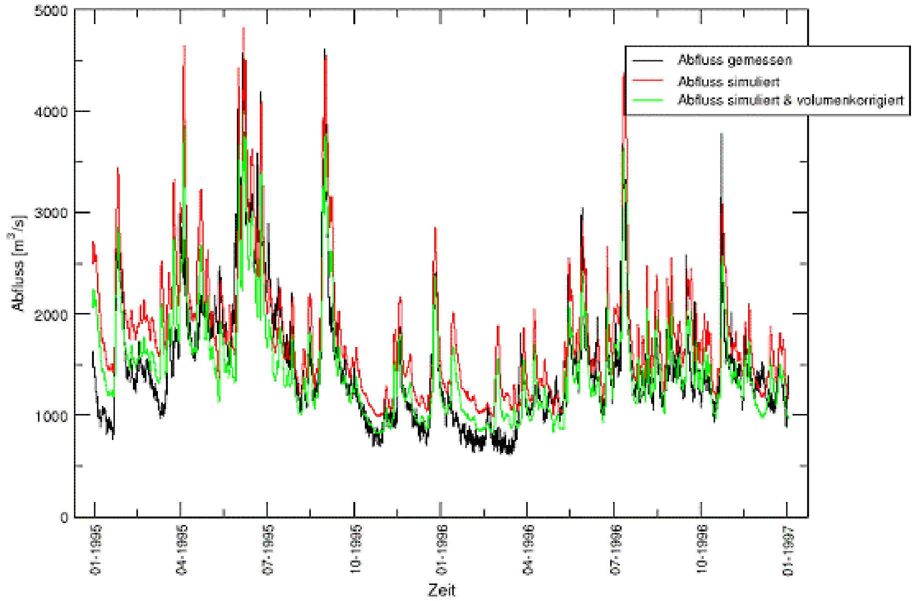

Figure 9: Measured and modeled river runoff (simulated and volume corrected) for the model period 01.01.1995 – 31.12.1996 at gauge Achleiten (76.660 km²).

The water temperature modeling in DANUBIA is based on the BLTM model (Jobson 1989) and does not require any calibration. Using proxelwise adopted air temperatures from the model component atmosphere, the water temperatures are determined based on the principle of the equilibrium temperatures. The fit between simulated and measured water temperatures at the gauge in Passau is quite satisfactory (figure 10).

By derivation of spatial information with remote sensing techniques the parameterization of the model subcomponents will be further improved and thus an essential contribution to the optimization of the results can be achieved.

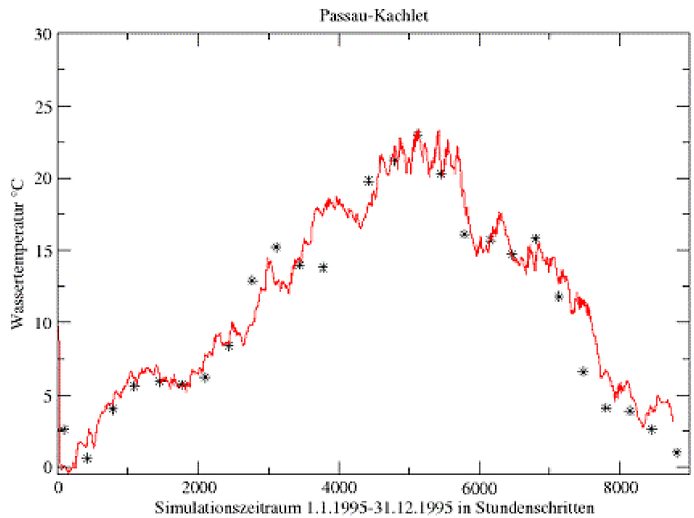

Figure 10: Measured and BLTM-modelled water temperature at gauge Passau-Kachlet for the year 1995.

4.4 Tourism

Within the project submodule "Tourism" the effects of tourism on the water cycle are investigated. In this respect, two main objectives are focussed: first, a model for the simulation of touristic water demand was developed with interfaces to the other project groups to quantify the touristic water demand under changing environmental conditions, and second a model of touristic attractivity was implemented which considers natural and derived factors of supply and their change during simulation time.

The use of water as a resource is realised in two different ways: first, water represents a commodity to be used for swimming pools, irrigation of golf courses snow making machines etc. Furthermore, water is used to preserve the touristic suprastructure: drinking water, cleaning water, and also water as touristic attractivity in the environment. In DANUBIA, a supply orientied approach was chosen, i.e. the water demand is determined by starting from the touristic water suppliers, here called actors. In the current model version, these actors are still restricted to predescribed behaviour. The next model version, which is currently in development, will allow the actors to decide themselves based on the environmental situation and the plans which they have available to adopt.

To quantify the touristic water demand, it was necessary to account for the demands of all types of touristic infrastructure and localise the respective actors in the catchment area (figure 10). The results shows that the touristic water demand is pointwise concentrated in the centers of tourism, i.e. only occurs in proxels with settlements. The model for the determination of both the infra- and suprastructural water demand account for the operation time of the touristic facilities and makes use of a database of accomodations and bed numbers based on official statistics. Total touristic water demand is calculated as the sum of infra- and suprastructural as well as day trip water demand. For 1998, total touristic water demand in the upper Danube catchment sums up to 40 Mio. m^3.

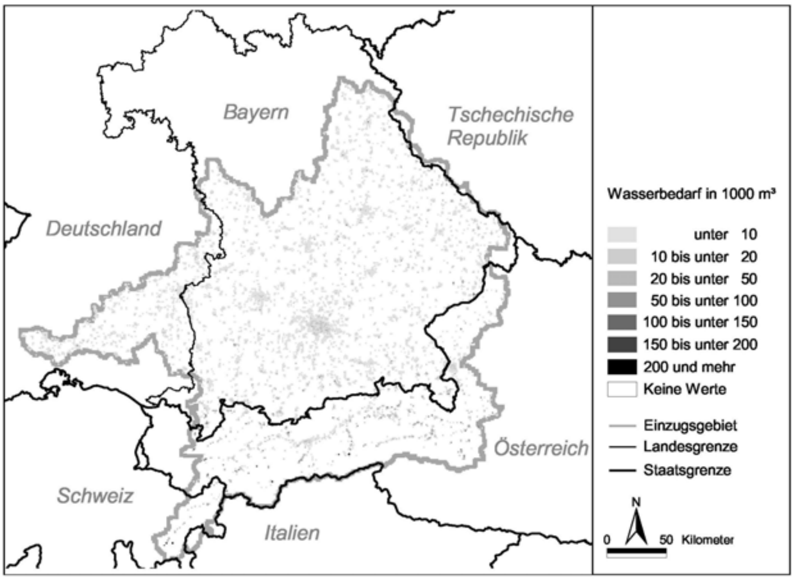

Figure 11: Touristic water demand in the Upper Danube catchment.

In the future, the model component for daily trip tourism will be adopted to the touristic attractivity of infrastructure. Therefore, all relevant facilities will be collected and localised. With the new concept of the deep actor it will be possible to let the actors find decisions based on the actual environmental situation during modelling time.

5. Conclusion and Outlook

The project GLOWA-Danube is a highly integrative scientific project. Within the first working period it has been shown that a web-based model integrating natural as well as socioeconomic sciences can be developed using an object oriented approach. Additional actor models for farming, tourism, drinking water supply and economy have been implemented. In the first validation runs, the model has proven the reliability of the concept and a correct representation of the processes governing the water balance in the catchment. The first scenario runs show the sensitivity of the system to changes in climatic input. Dry and respective wet periods reflect the expected effects on biomass production, the groundwater table, water management and tourism. In the second research phase the following tasks are planned: integration of stakeholders in a moderated dialogue to design scenarios and commonly discuss the results, direct coupling of the MM5 mesoscale meteorological model instead of the current atmosphere model that depends on data from meteorological stations, implement a deep actor framework for the socio-economic processes, and further develop and validate all the model components.

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