GLOWA-Danube: climate change and the future of water in the Upper Danube Basin

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Abstract

Within the framework of the joint research initiative GLOWA-Danube, the integrative decision support system DANUBIA is developed to support sustainable water resources management in the Upper Danube basin under conditions of global change. DANUBIA has to address a heterogenic catchment, natural and socio-economic processes, complex political and administrative structures and potential future developments in climate, demography and economy. Water balance and catchment runoff, agricultural land use distribution and water demand have been validated and the sensitivity of DANUBIA water fluxes to potential future changes of temperature and precipitation was tested. This paper addresses the structure of DANUBIA and recent developments in the representation of landsurface processes. Additionally, simulated daily river runoff is compared to gauge measurements.

Keywords: climate change, GLOWA, hydrology, integration, landuse, scenarios

1 Introduction

GLOWA-Danube (www.glowa-danube.de) is a joint research initiative funded by the Federal Ministry of Education and Research (bmb+f) to develop integrative techniques for supporting sustainable water resources management in the Upper Danube watershed under conditions of global change (climate, demography and globalised economy). For this purpose the global change decision support system DANUBIA has been implemented. It combines predictive models to simulate relevant natural and socio-economic processes. An interdisciplinary team of researchers from 13 different universities and institutions developed the current version of the system.

The main challenge in developing DANUBIA comes from (1) steep gradients and pronounced lateral flows in the mountainous watershed of the Upper Danube, (2) the sensitivity of the watershed to global change, (3) the complex political and administrative structure including five countries, two German states and two thousand water suppliers, and (4) the development of scenarios for future development in climate, demography and economy.

Similar approaches to integrated modelling of water resources are reported by Krol et al. (2006) and Liu et al. (2008) in the semi-arid regions of northern Brazil and the south-western United States. Another project investigating the impacts of climate change on the water cycle in southern Germany utilising meteorological drivers from climate models is KLIWA (www.kliwa.de). But these approaches lack the highly dynamic feedback between the physical and socio-economic process descriptions developed in GLOWA-Danube.

2 The Upper Danube Basin

The Danube is the second largest river in Europe with a watershed area of 817,000 km². GLOWA-Danube is limited to the analysis of the upper part of the catchment defined by the discharge gauge Achleiten near Passau in Germany (A ~ 77,000 km²). The Upper Danube basin consists of a mountainous part with altitudes up to 4,049 m a.s.l. and a large foreland (figure 1). Precipitation ranges from 650 to > 2,000 mm/yr and annual temperature from −4.8 to +9 °C.

Besides that, there are strong socio-economic gradients with different sources of income (industry, services, agriculture and tourism). The highly fragmented land cover and landuse is mostly determined by human activity. Forestry and agricultural use of different intensity (grassland, farmland) dominate, whereby the present agricultural potential is limited in various parts of the catchment due to climatic disfavours such as high precipitation and low temperatures.

The heterogeneous physiogeographic characteristics lead to a strong spatial and temporal differentiation of runoff generation. Regional floods occur frequently, triggered by convective summer rains in the alpine foreland and in the Alps. In addition, characteristic large-scale weather patterns combined with snowmelt activity can trigger floods affecting the whole Upper Danube region and its tributaries (e.g. the 200-years Pentecost Flood of 1999). For flood protection, energy production and management of water resources, the discharge of all important tributaries of the Upper Danube has been regulated with reservoirs and dams. The snow and ice storage in the Alps determine their management to a large extent. The Inn, as the most important alpine tributary, contributes up to 52% of the average discharge of 1,420 m³/s at gauge Achleiten. The Upper Danube is densely populated with about 8 Mio. inhabitants. The alpine part is mainly Austrian territory, while the foreland lies within the borders of the German states Bavaria and Baden-Würtemberg. Therefore water resources management is largely uncoordinated between the different administrative entities involved in power production and reservoir management (Barthel et al. 2005, Ludwig et al. 2003).

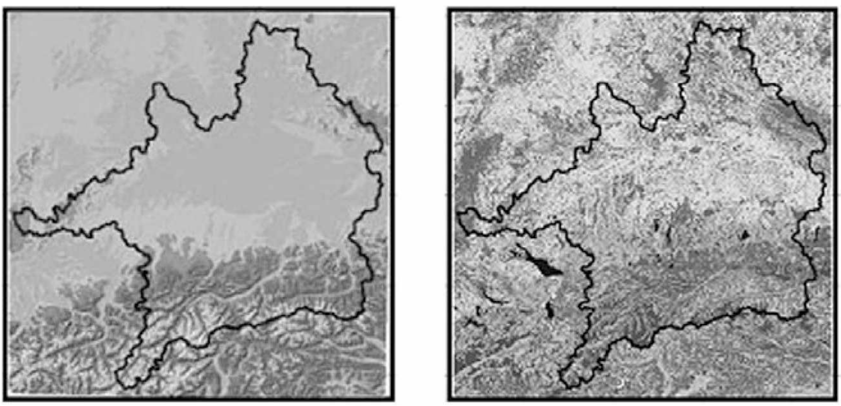

Figure 1: Topography and land cover of the Upper Danube basin.

3 The Decision Support System DANUBIA

DANUBIA is raster-based, object oriented and set up in JAVA and the Universal Modelling Language (UML) on an inexpensive LINUX-cluster (Ludwig et al. 2003). Both data and results of the system can be visualised by means of an interactive online tool. First validation runs (1971–2000) showed good results for the water balance and catchment runoff, agricultural land use distribution and water demand. A scenario run (2005–2050) with data from a stochastic climate generator showed the sensitivity of DANUBIA water fluxes to potential changes of temperature and precipitation.

The concept of scenario based decision support with DANUBIA (figure 2) regarding global change is based on scientifically sound meteorological input (Marke & Mauser 2008) and the dynamic representation of external factors. These factors include political and economical conditions as well as demographic and sociological trends inside and outside the catchment borders. Apart from influencing the scientific projections of regional development, stakeholders can formulate options and strategies for adaptation to and mitigation of impacts of global change regarding the future of water resources, landuse and tourism.

The next chapters delineate the integrative concept of GLOWA-Danube, the possible inputs for climate change scenarios and the recent advances of the landsurface process models that describe all important aspects of global change.

3.1 Integrative modelling techniques

A valid integration of all disciplines involved in GLOWA-Danube is crucial to the successful creation of the decision support system DANUBIA. Each project partner of GLOWA-Danube provides a well-established model of their scientific domain. These disciplinary models are highly sophisticated and specialised in their model core to account for the needs of disciplinary research. Competences outside of the model core, however, are usually less developed and often boundary condi-

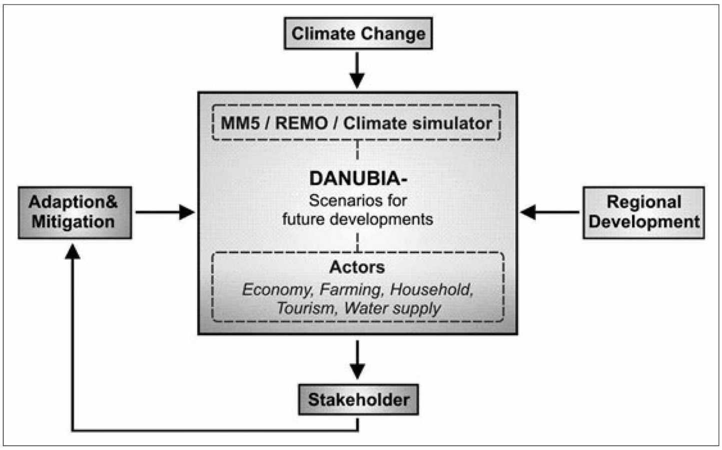

Figure 2: Abstract model of scenario based decision support with DANUBIA.

tions are described in a simplified way. Such models are not prepared dealing with complex questions and integrated scenarios. Within GLOWA-Danube integrative techniques have been developed and applied to overcome the mentioned deficiencies and to exploit the existing disciplinary expertise for a true integrative research of the water cycle (Ludwig et al. 2003). The basic spatial unit for all processes described in the DANUBIA system is the 1x1 km^2 process pixel ("proxel"). It enables the coupling of models on a common spatial platform and the exchange of 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 physical models to socioeconomic ones. A key to the approval of the proxel concept in the socioeconomic sciences is the commitment to agent based modelling (Ernst et al. 2008). In this approach, human activities are spatially resolved and represented by describing the varying preferences, decisions and the distinct behaviour of the actors.

Under the auspices of the computer science project group, a strictly object oriented, modular system (Hennicker & Ludwig 2006) was developed (figure 3). This enables DANUBIA developers to update their submodels with minimal effort and to disable submodels not relevant for their particular task. The Unified Modelling Language UML serves as a common language between the disciplines, and helps to explain the disciplinary models as well as to define unique core objects and interfaces between objects. 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 assignment of core competences allows a consistent description of all physical and socioeconomic processes (Ludwig et al. 2003). Each process is implemented once by the most competent group within the DANUBIA system. As a consequence each group can rely on the expertise of the other project partners and the entire project is benefiting most from each single discipline's expertise while avoiding unnecessary simplifications or even redundant modelling of the same processes.

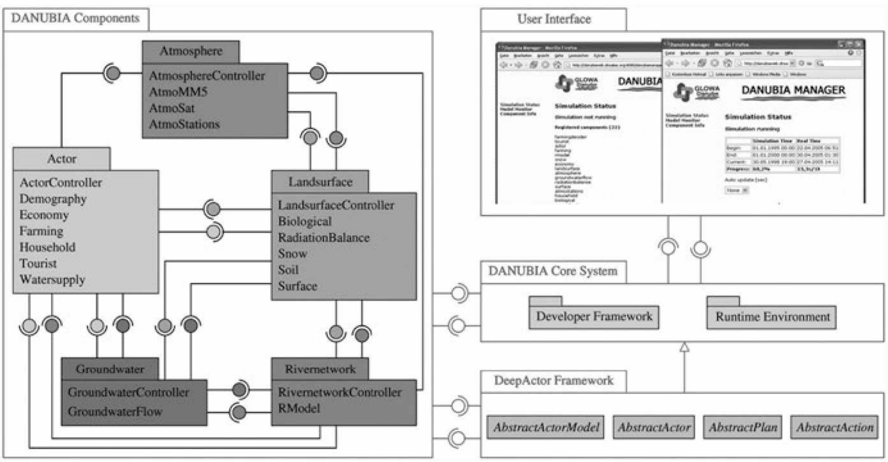

Figure 3: Components of the decision support system DANUBIA.

3.2 Sources of climate change scenarios

For the assessment of climate change impacts on the Upper Danube basin, two approaches to simulate future climate have been implemented. The first one is based on integrating regional climate models (RCM) via a bi-directional coupling tool with the DANUBIA landsurface component. As RCMs like Remo, MM5 or CLM work on different temporal and spatial scales not compatible with DANUBIA, the meteorological scaling tool SCALMET (Marke & Mauser 2008) has been invented. This tool conserves energy and mass fluxes even in alpine terrain. This allows for projections of climate change impacts on the basis of atmospheric models used in IPCC scenarios (IPCC 2007). The second approach to generate possible future weather trends is to generate meteorological time series with the stochastic weather generator integrated in DANUBIA. It rearranges historically measured meteorological records from the period 1970 to 2003 with the same temporal and spatial resolution as the input data used for validation. The method is based on the assumption that a climate period can be decomposed into months characterised by an average temperature $\overline{T}$ and a precipitation sum $\overline{P}$. $\overline{P}$ is assumed a function of $\overline{T}$. After a statistical analysis of the measured monthly precipitation and air temperature values of 1970 to 2003, a mean value of $\overline{P}$ and $\overline{T}$ for each month of the year is available, and the covariances between these two variables for each month are known.

These parameters represent the intrinsic dependencies between temperature and rainfall for each month in the year. The weather data for each month of the synthetic time series is chosen by a randomly generated $\overline{T}$, while $\overline{P}$ is chosen by another random number and the covariance between $\overline{T}$ and $\overline{P}$. By imposing a positive temperature trend shift on the result of the first random number selection a series of monthly increasing temperatures can be simulated. This procedure ensures that the original relationship between temperature and rainfall is preserved in the meteorological time series of the selected climate scenario. Finally, the month most closely fitting the randomly selected pair of $\overline{T}$ and $\overline{P}$ is selected from the historical data using a Euclidian nearest neighbour distance metric (figure 4).

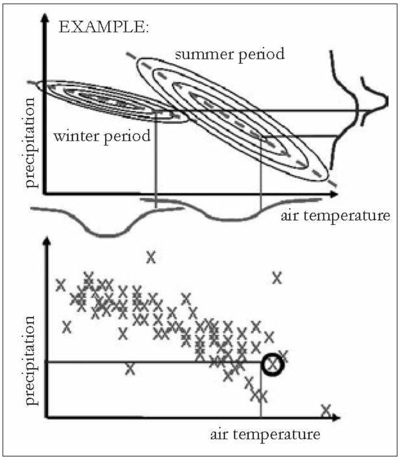

Figure 4: Procedure of the deriving future climate data with the stochastic weather generator

3.3 Recent advances in mesoscale landsurface modelling

The most recent developments for the landsurface component in DANUBIA have been designed to improve the ability to address the requirements of a transdisciplinary global change decision support system at the regional scale, heading for a 50 years future scenario horizon. Besides the implementation of hydraulic structures in the river network model, the biggest effort of the project group "Landsurface" was to improve the process descriptions of the energy and water fluxes between land surface and atmosphere. Another main focus was the improvement of simulated water storage as snow and ice in alpine environments. The following papers in this issue show the current results of these improvements.

The main area of recent improvements of the landsurface model has been the closing of the surface energy balance by integrating (bio-)physical models of coupled water and energy processes in plants, snow and soil (Hank & Mauser 2008, Prasch et al. 2008, Muerth & Mauser 2008). Besides simulating more realistic energy transfer from the landsurface to the atmosphere, the improvements also led to a more physically based description of water and matter fluxes in plants, soil, snow and glaciers. For the sensitive high alpine regions a subpixel scale glacier model was developed, that has shown realistic glacier dynamics as well as a subscale snow distribution model for alpine regions (Prasch et al. 2008). The explicit consideration of soil temperature and soil freezing improves the prediction ability of DANUBIA of biochemical cycles like the nitrogen cycle, the computation of soil evaporation and the formation of lateral runoff due to ice blocking (Muerth & Mauser 2008). The plant physiological model implemented in the framework has shown its ability to react on climate change in contrast to static evapotranspiration algorithms. Especially important for alpine regions, first scenario runs show an significant trend towards earlier leaf growth and a prolonged vegetation period for the Alpine forests (Hank & Mauser 2008). Regarding matter fluxes, an erosion, transport and deposition model of soil particles is currently being implemented into DANUBIA. The results of physically based erosion models are highly sensitive to rainfall intensities, which are generally smoothed when interpolating meteorological data from climate stations. Hence a temporal disaggregation algorithm estimating precipitation in 10-minutes intervals was developed (Waldmann & Mauser 2008).

4 Result of the Danube simulation

DANUBIA was applied to the Upper Danube catchment for the period of 1970–2003 to show its principle applicability for regional global change studies. For this purpose any calibration of the model was avoided to guarantee a proper reaction to future climate states that may not be covered by present conditions. Routing of river runoff is computed by a modified, raster-based *Muskingum-Cunge* method as modified by Todini (2007). The river network submodel of DANUBIA also includes retention of water at man-made, hydraulic structures (dams, reservoirs, etc.). Meteorological data from the German and Austrian networks were used as historical meteorological drivers for DANUBIA (Mauser & Bach 2008).

As can be seen in figure 5, the general course of discharge at the gauge Achleiten near Passau is well captured. Nevertheless the peak discharge is usually overestimated in the time series. To more closely validate the performance of DANUBIA selected sub-catchments were analysed. This documents the scaling properties of the model when going from the whole catchment to smaller sub-entities (Mauser & Bach 2008).

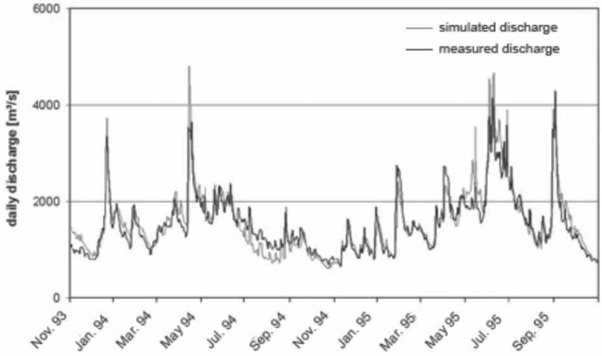

Figure 5: Discharge at gauge Achleiten (basin outlet) for the hydrological years 1994–1995

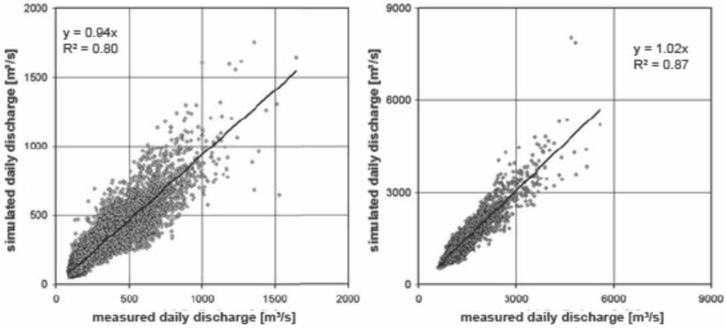

Figure 6: Correlations of daily discharge at gauges Oberaudorf (Inn) for 1971–2000 and Achleiten (Upper Danube) for 1991–2000

Figure 6 shows the daily correspondence between measured and modelled discharges in the Inn catchment for a 30-years time span. Despite the complex alpine terrain and many hydraulic structures along the course of the Inn, an R^2 of 0.80 was achieved. Because of the less dynamic runoff generation in the non-alpine parts of the catchment, the discharge at the outlet of the Upper Danube basin is more closely simulated ($R^2 = 0.87$), as shown in figure 6 for the hydrological years 1991 to 2000. The results show that DANUBIA can be used to study the impact of future climate scenarios in the regional water cycle in the Upper Danube basin.

5 Outlook

In the third and last project phase we will comparatively utilise output of the regional climate models MM5, Remo and CLM and the statistical climate generator to study the impacts of a changing climate. In interpreting the results, carbon, phosphate and nitrogen fluxes as well as erosion will be added with special focus on the interrelationships and mutual dependencies between the different natural and societal components of the system, hydrological extremes and risk assessment as well as mitigation strategies. At the end of the third project phase in 2010, DANUBIA will be given to the public as an Open Source software tool.

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