Abstract

Global Climate Change will have regional impacts on the water resources and will force water resources managers and farmers to adapt. Both low-flow and its duration are critical hydrological parameters, which strongly influence the state of aquatic ecosystems as well as power production, reservoir management and industry. Impacts of future climate change is analysed using scenarios for the change of meteorological drivers and regional hydrologic simulation models. The project GLOWA-Danube (www.glowa-danube.de) develops integrative modelling techniques combining process knowledge from both natural and social sciences to examine the sustainability of regional water systems as well as water management alternatives in the Upper Danube watershed (A = 77000 km²). Special emphasis is given to changes in low-flow condition.

DANUBIA describes the regional water cycle both physical and spatially distributed. It consists of a collection of tightly coupled models, which strictly preserve energy and matter and are not calibrated to maximise their overall predictive abilities. The paper demonstrates that DANUBIA can reproduce the daily discharge for the time period from 1970-2005 with a Nash-Sutcliffe coefficient of 0.84 (gauge Achleiten). Based on a statistical climate simulator 12 realisations of the IPCC A1B climate scenario were used to investigate impacts of climate change during the simulation period of 2011–2060. The change in discharge and frequency of occurrences of low-flow in the watershed for the scenario ensemble were analysed for the outlet gauge. The analysis shows that strong changes were simulated in the frequency of occurrences of low-flow conditions. The changing climate gradually reduces a 50-years NM7Q discharge of today to less than half of its discharge in the year 2060. These results clearly indicate that the expected climate change will strongly alter the low-flow conditions in the Upper Danube watershed.

Keywords: climate change, mountain hydrology, PROMET, low-flow.

1 INTRODUCTION

Conditions of low-flow are an important limiting factor for the utilization of water resources. Low-flow is characterized by a prolonged below average discharge in a river system. The reasons for low-flow can be manifold. They range from reduced rainfall, elevated evapotranspiration, reduced water storage or cold temperatures with freezing soils and water or natural water storage in mountain snow packs. Usually only a combination of reasons creates severe low-flow conditions. Severe low-flows can impose limitations on those water dependent infrastructures, which use river water, e.g. hydropower production, cooling in the process of conventional power production and navigation. Low-flow can therefore cause substantial financial losses since the
installed structures either shut down or have to adapt their operation to the limitations created by the missing flow.

Low-flow augmentation can be achieved through reservoirs, which collect runoff and release it during times of droughts. Reservoirs and their operation therefore are an important component of the overall water infrastructures in a basin.

From a global perspective climate change is usually perceived as an increase in average air temperature, which is assumed to be well predictable both in its magnitude and spatial distribution. When it comes to the expected changes in rainfall predictions are much less certain. For the case of Central Europe IPCC expects no significant changes in annual rainfall but significant increases in rainfall amounts in winter and corresponding decrease in summer. How serious will be the effects of changing climatic drivers on the regional water cycle and what are suitable adaptation strategies for the water infrastructures are important questions in the context of regional impact studies of Global Change?

A case study with the aim to analyse the expected changes in low flows was conducted within the interdisciplinary research project GLOWA-Danube (www.GLOWA-Danube.de) to exemplify both the power of DANUBIA as a scenario tool and the regional impacts of climate change on the complex, large, mountainous watershed of the Upper Danube in Central Europe. The water cycle components of DANUBIA are set up as a spatially distributed, physical hydrological model, which conserves mass and energy and which is not calibrated against measured historical runoff (Mauser and Bach 2008).

The paper is set up as follows: first the Upper Danube watershed and the trends in climate change, which have already occurred there are introduced, second the general approach of GLOWA-Danube and the integrated Global Change decision support system DANUBIA is described and checked against measured historical stream flows, third a statistical climate change simulator, which produces possible future time series of meteorological drivers using already measured data is introduced and fourth the impact of an ensemble of climate realisations for the next 50 years on the low flow conditions of the Upper Danube watershed is demonstrated.

2 THE UPPER DANUBE WATERSHED

2.1 The Geography of the Upper Danube

In order to validate DANUBIA it is applied to the Upper Danube catchment. The Upper Danube catchment covers an area of 76,653 km² and is situated in parts of Southern Germany, Austria, Switzerland and Italy (Fig. 1). The catchment is characterized by its Alpine topography, the relief stretching from altitudes of 287 m a.s.l. at the discharge gauge Achleiten up to 4049 m a.s.l. at Piz Bernina in its Alpine headwaters. The Upper Danube catchment shows strong meteorological gradients with annual precipitation ranging from 550 to more than 2000 mm, an annual mean temperature from -4.8 to 9°C, evapotranspiration from 100 to 700 mm per year and annual discharge from 150 to 1750 mm per year. Geology is dominated by the northern rim of the Alps with a sequence of mountain ridges composed of granite, limestone to
sedimentary rocks. The lowlands north of the Alps are composed of moraine material deposited during the last ice ages and a sedimentary basin, which is up to 3000 m deep. Most rivers emerge in the Alps and cross the lowlands towards the North to feed the Danube, which flows in W-E direction in the northern part of the watershed. Soils are very heterogeneous ranging from coarse soils in and close to the Alps to deeply weathered fine-grained soils in the lowlands of the Danube. As a result of all heterogeneities the land use and land cover pattern is highly diverse: it ranges from glaciers in the upmost headwaters through large conifer and deciduous forests and meadows in the Alpine valleys and on the moraines to intensively managed meadows and agricultural areas (maize, cereals, potatoes, sugar beet) in the valleys of the lowlands (Ludwig et al., 2003b). North of the river Danube the catchment is framed by the mid-altitude mountains of the Bavarian Forest and the Swabian Alb.

Figure 1: The Upper Danube Watershed

The water resources in the Upper Danube are intensively used by 4 countries and 5 States. Most river runoff in the catchment is managed either for hydropower production through run-of-river power stations, water diversions, cooling of power plants or large reservoirs, which in the Alps are mainly used for low-flow augmentation during the winter period. The water resources of the Upper Danube, which are not consumed within the watershed through evapotranspiration or through water diversion into other watersheds (e.g. Main) are released to the downstream Danube countries. They strongly depend on the water surplus of the Upper Danube for power production, irrigation and navigation.
2.2 Climate Change in the Upper Danube Watershed

The Upper Danube has already undergone considerable regional climate change. A thorough analysis of the temperature increases, which have already occurred, was conducted in the GLOWA-Danube project in order to compare global climate trends as forecasted by the IPCC with regional effects. The analysis is based on the record of 277 meteorological stations in the watershed from the German and Austrian Weather service and uses the record from 1960 to 2006. Fig. 2 shows the result of the analysis. It can be seen clearly that air temperatures in the watershed have already increased from 7.2 °C in 1960 to 9.2 °C in 2006. This strong increase can only be explained by the IPCC A1B scenario if one assumes, in accordance with IPCC, that the regional increase in air temperature can deviate strongly from the global mean. For the Upper Danube the assumption that the regional increase in air temperature is larger than the global increase by a factor of 1.7 explains the observed curve in the past and leads to the regression line in Fig. 2. Fig. 2 shows that the temperature increase also applies to the annual monthly minima and maxima. Using the assumption of Fig. 2 a statistical climate generator produced future possible climate time series (red), which follows three conditions: 1) it is statistically equivalent to the measured data from 1970-2006 in that it considers the temporal development of the statistical relation between mean weekly temperature and rainfall sums over the year, 2) it considers coupled standard deviations of both temperature and rainfall through a random number generator, 3) it considers the IPCC A1B temperature trend over the next 55 years multiplied by a factor of 1.7.

Figure 2: Past and future trends in air temperature for the Upper Danube catchment based on the IPCC A1B scenario.
The way the climate scenario information is used within DANUBIA to evaluate the consequences of a changing climate on the low-flow conditions in the Upper Danube watershed is shown in principle in Fig. 3.

Fig.3: Schematic diagram of the utilization of the Global Change Decision Support System DANUBIA for the stakeholder dialogue within the GLOWA-Danube project

Fig.3 shows that two main drivers affect the future development of water management in the Upper Danube watershed. First there is climate change. It acts upon DANUBIA through climate scenarios originating from different sources. Currently results from regional climate models like MM5 and REMO can be assimilated into DANUBIA. The second driver is regional development, which includes demographic change, economic development, changing EU-regulations as well as external (global) boundary conditions. Regional development influences the decisions of actors in DANUBIA. Actors are self-contained entities, which make decisions. They receive information on their environment, have plans for actions and experiences from past actions. Actors can be different groups of society, the decisions of which are simulated. Currently DANUBIA contains farmers, households, water suppliers, tourists and industrial branches. The decisions of the actors as well as changing climate simultaneously influence the water flows in the Upper Danube watershed leading to a complex web of interactions, which result in a future change of the water balance in the watershed. Key factors for change are characterized by changing land use (through farmers’ decisions), melting glaciers, reduced snow cover, changing reservoir operations, etc. The presented paper concentrates on the influence of changing climate alone and takes the first order assumption that land use, demography, water consumption etc. will not change during the modelling period from 2011 to 2060.

As Fig.3 shows the results of the scenario simulations are presented to interested stakeholders. In an interactive process the results are discussed with the stakeholders and ways to both regionally adapt to climate change and to mitigate causes of the changing climate are elaborated by the stakeholders. They are implemented in DANUBIA and lead to a new scenario run. The efficiency and effectiveness of the
proposed decision alternatives are then discussed with the stakeholders in a second iteration.

3 PROMET – THE HYDROLOGICAL MODEL BEHIND DANUBIA

The investigation of the impacts of climate change on the regional hydrology needs predictive hydrologic models, which include physical descriptions for all compartments of the regional water cycle. PROMET was developed as a raster model with 1x1 km raster elements. Fig. 4 shows a schematic diagram of the compartments represented in PROMET. The basic principles, which were followed in the design of PROMET (Mauser and Bach (2008)) were:

1. a fully physical and physiological description of the water fluxes in the compartments of complex watersheds of medium size (A~100 000 km²). The different components of PROMET should be fully coupled. The components are:
   a. meteorological drivers either from regional climate models or from station data,
   b. land-atmosphere energy and mass exchange based on plant physiologic control of gas exchange (interception of rainfall, evapotranspiration, sensible heat exchange, carbon uptake or release, long- and shortwave radiation balance as well as momentum exchange),
   c. snow and ice accumulation and ablation,
   d. vertical and lateral unsaturated and saturated flows including infiltration
   e. channel flow and flow through lakes,
   f. flow through man-made reservoirs and water transfers.

2. PROMET should strictly conserve mass and energy as a whole and within as well as throughout all its components and feedbacks.

Fig.4: Schematic diagram of the compartments of PROMET
3. PROMET should be spatially explicit in all process descriptions. In order to be most compatible with models from other disciplines (e.g. regional climate models, carbon models, groundwater models, multi-agent raster-based decision models) the spatial representation in PROMET is based on an isotropic grid. A watershed is composed of a set of raster elements, which exchange data with their surrounding and all processes treated within PROMET are consequently described based on the same set of raster elements.

4. Physical consistency and predictive power should not be diminished or lost in the model calibration process. Therefore the values of the model parameters of PROMET should not be calibrated using measured discharge at gauges in or at the boundary of the considered watershed. Instead we use literature sources and/or measurements (both in the field and from remote sensing sources) and a detailed analysis of the digital terrain model to define the initial values of all model parameters.

4 VALIDATION OF PROMET

Fig.5 shows the resulting daily discharge modelled for the period between 1971 and 2003 for the Passau gauge close to the outlet of the 77000 km² watershed. As can be seen clearly the daily discharge is modelled with a high accuracy. Fig. 2 shows the measured and modelled annual low-flow, which is defined as the annual minimum 7-days average flow for the same gauge for the same period. The annual variability of low-flow is well captured by the model for historical periods.

Fig.5: a) Measured and modelled annual low-flow (minimum 7-days average discharge) for the reference period of 1971-2003 at Passau gauge, Upper Danube watershed; b) Measured and modelled daily discharge for the reference period of 1971-2003 at Passau gauge, Upper Danube watershed.

Tab. 1 shows the results of the validation runs for selected gauges in the Upper Danube watershed representing watersheds of different areal extents and hydrologic conditions. The Salzach as well as the Inn are two tributaries of the Upper Danube which are strongly influenced by the hydrologic regime of the Alps. Under current climate conditions this means that discharge is low in winter due to snow storage and large in spring and early summer due to snow melt. The Naab and Ammer are tribu-
taries, which are not or hardly influenced by Alpine hydrology. Tab. 1 therefore covers a broad range of watersheds with very different hydrologic conditions. As can be seen slopes of the 1:1 regressions, as shown in Fig. 5b, are close to 1.0 and the coefficient of determination $R^2$ is high throughout all watersheds. So is the Nash-Sutcliffe coefficient with the one exception of the Isar. There the Sylvenstein reservoir, which is operated in a manner, which is not transparent to the authors is strongly affecting discharge.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>River</th>
<th>Upstream Area [km²]</th>
<th>Slope [-]</th>
<th>$R^2$</th>
<th>Nash-Sutcliffe Coefficient [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achleiten</td>
<td>Danube</td>
<td>76 673</td>
<td>1.03</td>
<td>0.87</td>
<td>0.84</td>
</tr>
<tr>
<td>Hofkirchen</td>
<td>Danube</td>
<td>46 496</td>
<td>1.11</td>
<td>0.87</td>
<td>0.81</td>
</tr>
<tr>
<td>Dillingen</td>
<td>Danube</td>
<td>11 350</td>
<td>1.13</td>
<td>0.84</td>
<td>0.72</td>
</tr>
<tr>
<td>Oberaudorf</td>
<td>Inn</td>
<td>9 715</td>
<td>0.94</td>
<td>0.81</td>
<td>0.80</td>
</tr>
<tr>
<td>Plattling</td>
<td>Isar</td>
<td>8 435</td>
<td>1.08</td>
<td>0.75</td>
<td>0.47</td>
</tr>
<tr>
<td>Laufen</td>
<td>Salzach</td>
<td>6 112</td>
<td>0.86</td>
<td>0.85</td>
<td>0.80</td>
</tr>
<tr>
<td>Heitzenhofen</td>
<td>Naab</td>
<td>5 431</td>
<td>0.99</td>
<td>0.78</td>
<td>0.79</td>
</tr>
<tr>
<td>Weilheim</td>
<td>Ammer</td>
<td>607</td>
<td>0.98</td>
<td>0.63</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Tab. 1: Selection of gauges within the Upper Danube watershed. Achleiten is at the outlet of the Upper Danube near Passau.

5 CLIMATE IMPACT ON LOW-FLOW – SCENARIO INVESTIGATIONS

5.1 The Synthetic Climate Generator

Based on these results the period from 2011 to 2060 was modelled using the output of a stochastic climate generator. It uses the IPCC-A1B scenario with the empirical multiplication factor of 1.7 for the regional trends of temperature increase in the Upper Danube watershed. This regional adaptation of the IPCC A1B scenario results in a 3 degree temperature increase in the Upper Danube watershed until the year 2060. A random number generator, which is based on the covariance matrices of weekly mean temperatures and rainfall sums generates pairs of deviations from a mean temperature and rainfall sum for each week in the period between 2011 and 2060. These values together with the IPCC temperature trend produce pairs of statistical mean temperature and rainfall sum for each week from 2011 to 2060. For each future week a minimum distance algorithm then searches for the most similar meteorological data set in the measured data from 1960-2006. Through this procedure a synthetic time series of meteorological input data is produced, which 1) confirms to the statistical behaviour of the past (one necessary but critical assumption) and 2) reflects the regional temperature trend of IPCC.

This synthetic climate generator can easily be used to create a large number of statistically equivalent future climate data sets by changing the seed for the random
number generator an re-running the procedure. In order to evaluate the uncertainty of the estimated change in low-flow an ensemble of 12 different realisations of the same IPCC A1B climate scenario was modelled and analysed. The following strategy was applied:

1) for each of the 12 realisations a different story was developed to select the valid realisation from a large number of simulated meteorological time series. A story in this context is a set of assumptions about the future, which can be converted into rules to select a certain realisation of a scenario.

2) Based on the assumption 5000 meteorological data sets were produced with different seeds for the random number generator.

3) The 5000 meteorological data sets were analysed statistically according to the underlying assumptions of the stories formulated under 1) and the realisation, which fulfilled the assumption with a probability of 1% was selected.

The described procedure was applied for the following stories:

<table>
<thead>
<tr>
<th>Realisation</th>
<th>Story</th>
<th>1% Rainfall [mm]</th>
<th>1% JJA-Temp. [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No change in air temperature until 2060</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Min. rainfall sum of 5 consecutive years between 2011-2035</td>
<td>4015</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Min. rainfall sum of 5 consecutive years between 2036-2060</td>
<td>3883</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Min. rainfall sum of 3 consecutive years between 2011-2035</td>
<td>2517</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Min. rainfall sum of 3 consecutive years between 2036-2060</td>
<td>2387</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Min. rainfall sum of 1 year between 2011-2035</td>
<td>791</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Min. rainfall sum of 1 year between 2036-2060</td>
<td>762</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Average rainfall between 2011-2035</td>
<td>1027</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Average rainfall between 2036-2060</td>
<td>922</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Max. aver. JJA temp. of 5 consecutive years 2011-2035</td>
<td>20.15</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Max. aver. JJA temp. of 5 consecutive years 2036-2060</td>
<td>20.35</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Max. aver. JJA temp. of 1 year between 2011-2035</td>
<td>21.62</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Max. aver. JJA temp. of 1 year between 2036-2060</td>
<td>21.7</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 2: List of the realisations 1-12 together with the zero-hypothesis that temperature will not change in the future. Column 2 expresses the story, columns 3 and 4 give values for total rainfall or mean temperature for the period under consideration.

5.2 Effects of Climate Change Scenarios on low-flow

For all selected scenarios together with one scenario, the zero-hypothesis, which assumes that no further change in temperature will occur in the future, the water flows were modelled on an hourly basis for the period from 2011 to 2060 using DANUBIA. The resulting hourly runoff data was aggregated to daily values for the outlet gauge in Aichleiten. The resulting discharge records were analysed for the lowest annual mean 7-days discharge (NM7Q), which was selected as criterion for low-flow conditions. The time series of annual low flows is shown in Fig.6. The left part of Fig.6 shows the modelled and measured historical low flows from 1970 to 2003. As can be seen clearly there is considerable scatter both in the measured and modelled data. The right hand side of Fig.6 shows the development of the annual low flow for the period from 2011 to 2060 for realisation 0 to realisation 12 in Tab.2. As can be seen clearly the zero-hypothesis of no temperature increase in the future leads to no sig-
nificant changes in the simulated future annual low-flow. On the other hand the assumed temperature increase leads to a considerable reduction of simulated annual low-flows for all selected stories of the IPCC A1B scenario. As can be expected there also is a considerable annual scatter in the development of low-flow. This means that it may well be that in 2050 there could be an annual low-flow occurring, which is as high as today’s. Nevertheless the general trend of decreasing low-flows is obvious.

Fig. 6: Annual low-flow (min. 7-days mean discharge) from 1970-2005 and from 2011-2060 at gauge Achleiten using the 12 realisations of the IPPC A1B scenario as listed in Tab. 2

Fig. 7: Development of the 50-years return period NM7Q low-flow condition at gauge Achleiten; blue = determined from measurements, green = no climate change, red = average from realisation 1-12 from Fig. 6
Fig. 7 shows the result of an analysis of the course of the 50-years return period low-flow condition at gauge Achleiten. The blue, green and red curves were determined using a 25 years window, which was shifted over the measured and modelled data. For each window the 50-years low-flow was determined by fitting a log-normal distribution to the annual low-flow data and determining the minimum annual 7-days average discharge with 98% excess probability (NM7Q50). The blue curve in Fig. 7 represents the change in measured data, the green curve stands for the temporal development of the NM7Q50 when no temperature increase occurs and the red curve represents the change in NM7Q50 when assuming the average development of the annual low-flows of all realisations shown in Fig. 6. As can be seen clearly 1) the simulated 50-years return period low flow hardly changes in the future when assuming no change in the air-temperature and the related rainfall, 2) NM7Q50 decreases sharply and is reduced to half of its present value by 2030 and to one third of its value by 2060 when investigating the effects if a series of realisations of the IPCC A1B climate change scenario. This indicates a change in flow regime in the discharge of the Upper Danube since low-flows with such a discharge have not yet been measured.

6 CONCLUSIONS

The simulations of the effects of an ensemble of different statistically equivalent realisations of the IPCC A1B climate change scenario on the low-flow conditions have shown that, following the assumptions of the statistical climate generator described above, severe changes in the low-flow conditions in the Upper Danube can be expected in the future. They range from a reduction of the expected low-flows to half of their present discharges by 2030 to a reduction to one third of their present values by the year 2060. The reasons for the steep reductions are manifold and interrelated in a complex manner. The main reasons are: 1) the changes induced in the snow cover in the Alps. With increasing temperatures an increasing fraction of today’s snowfall will fall as rain, will run off during the winter season and not be stored in the Alps; 2) the decreasing summer rain fall, 3) the increasing evapotranspiration. All three factors work towards a reduction of low-flow in summer and amplify each others.

It can be expected that the reduction of low-flows will have a notable impact on water resources management both within the Upper Danube watershed and downstream. More frequent and severe low-flows will mainly affect power-production and transportation. Future investigations will concentrate on possible adaptation measures to compensate for the changes in low-flows in the Upper Danube. Measures like changes in land-use or the increase of managed storage capacity in the watershed as well as changes in the operation of existing reservoirs will be investigated.

7 ACKNOWLEDGEMENT

The authors wish to thank the German Ministry for Education and Research, the Free State of Bavaria and LMU Munich for funding the GLOWA-Danube project. Thanks also go to the German and Austrian Weather Service as well as the Bavarian State Authority for the Environment (LfU) for the supplied data.
References