Adapting to Water Scarcity in Europe

Wolfram Mauser and Tobias Hank

Abstract

According to IPCC projections Europe will experience considerable changes in rainfall amounts and distribution during this century. This would lead to an increasing polarisation of water availability between the north, where rainfall amounts are expected to increase and the South, where they may sharply decrease. Results from a coupled regional climate impact model, which simulates the reaction of the runoff regime of the mountainous Upper Danube river basin on the expected climate change, demonstrates as a case study, that a complete change in the hydrologic regime of Central and Southern European mountain water resources is likely. The consequences, more severe low-flow conditions, sharply decreased summer discharges, reduced hydropower potential and an increasing demand for irrigation, are demonstrated. Possible ways to adapt by changing the operational mode of existing reservoir structures are discussed.

Keywords: climate change, mountain hydrology, PROMET, runoff regime

1. Introduction

Global Climate Change will have regional impacts on the water resources in Europe (IPCC, 2007). The regional IPCC-projections for the course of this century split the impacts between Southern Europe, where a considerable reduction of rainfall and warmer summers are predicted and into Northern Europe, where rainfall will increase and especially the winters will become warmer. This projection is based on the results of global climate models and suggests that the predicted temperature increase will extend the Mediterranean influence further north and intensify the circulation pattern over Northern Europe. This leads to the likely conclusion that water scarcity will not be the major problem for Northern Europe. As in the past, water scarcity will unfortunately remain the problem of Southern Europe and it will most likely intensify there. Nevertheless the runoff regime of the Mediterranean rivers will very likely not change in the future due to the persistence pattern of predominant rain in winter and drought in summer. Therefore this region of Europe can rely on proven infrastructure, which was established in the form of reservoirs and irrigation systems to adapt to this climatic pattern and to balance water availability over the year and to guarantee the hydrologic basis for manifold economic activities although climate change will put increasing pressure on water resources and will therefore also influence energy production and agriculture in the Mediterranean region.

Between the North and the South of Europe lies the transition region of Central Europe. This region, which includes the Alps and extends around 45 degrees North is influenced climatically both by the Westerlies in winter and the Mediterranean high pressure systems in summer. This region is currently characterized by cool to cold winters and a summer rainfall peak, which feeds evapotranspiration when its demand is highest. This climatic pattern currently shows no water scarcity, supports high yield rain-fed agriculture and is optimal for run-of-river hydropower production. What will be the consequences of climate change on the water availability in this climatic transition region of Europe? Climate change will most likely increase the Mediterranean component of the regional climate. In accordance to IPCC (2007) rainfall will increase in winter and decrease in summer. This makes it likely that these regions may experience a complete change in the hydrologic regime from a summer rain region into a winter rain region.

GLOWA-Danube (www.GLOWA-Danube.de) is an interdisciplinary projects which aims at investigating the impact of climate change on the hydrology of the Upper Danube basin (A = 77000 km²), which includes parts of the Alps and their northern forelands. The Upper Danube is situated in the transition zone between the Mediterranean and Northern European climate region. The paper will focus on the question, whether a change in hydrologic regime will likely occur in the Upper Danube as a consequence of climate change and whether this change in regime will result in water scarcity. We choose to investigate the likely change in low-flow and emerging plant water stress as a criterion for the analysis. 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 in the watershed. Impacts of future climate change in low-flow is analysed using scenarios for the change of meteorological drivers and the regional hydrologic simulation model PROMET (Mauser and Bach (2008)).

PROMET was specifically developed to study the impacts of climate change on the regional water cycle and is both physical and spatially distributed. It consists of a collection of tightly coupled models, which strictly preserve energy and matter and are not calibrated in order to maximise their overall predictive abilities. The paper demonstrates that PROMET can reproduce the daily discharge for the time period from 1970-2005 with a Nash-Suttcliffe 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 flow regime and both discharge and frequency of occurrences of low-flow in the watershed were analysed for the scenario ensemble at the outlet gauge.

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 PROMET it is applied to the mountainous Upper Danube watershed. It covers an area of 76 653km² and is situated in parts of Southern Germany, Austria, Switzerland and Italy (Fig. 1). The Upper Danube relief stretching from altitudes of 287 m a.m.s.l. at the discharge gauge Achleiten up to 4049 m a.m.s.l. at Piz Bernina in its Alpine headwaters. This induces 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.

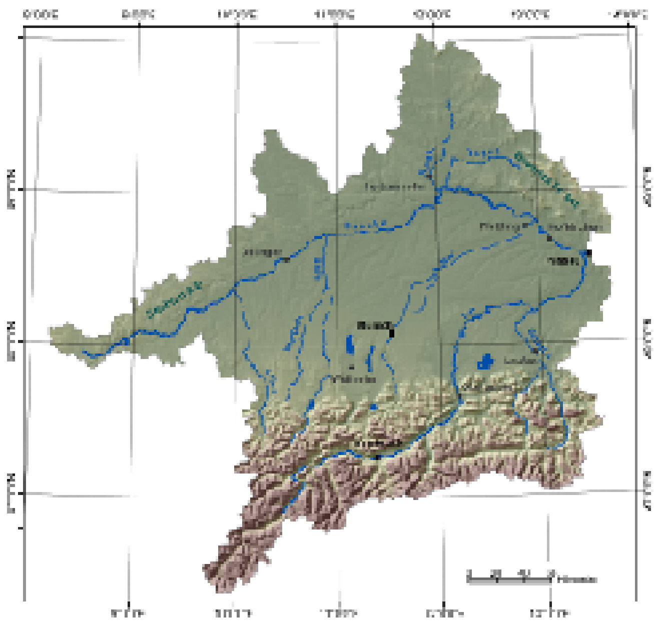


Figure 1. *The Upper Danube Watershed*

Most rivers in the Upper Danube basin 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 low-lands of the Danube. This overall heterogeneities results in a highly diverse land use and land cover pattern: 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.

The water resources in the Upper Danube are intensively used by four countries and five 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 currently 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 8.6 °C in 2006. This strong increase can only be brought in correspondence with the global 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.

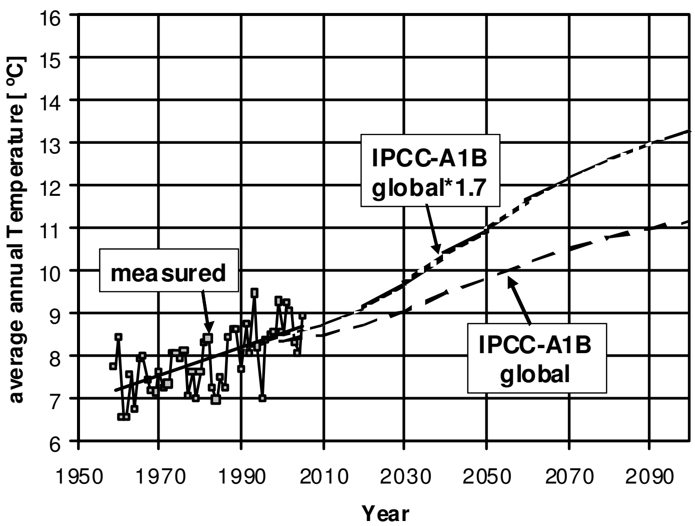


Figure 2. *Past and future trends in air temperature for the Upper Danube catchment based on the IPCC A1B scenario.*

2.3. The climate change decision support system DANUBIA

The climate change decision support system DANUBIA was set up in order to make climate impacts and the reactions of important actors in the Upper Danube watershed more transparent for water resources managers. DANUBIA consists of interfaces to different sources of regional climate change information like the regional climate models MM5 and REMO or a stochastic climate change scenario generator. It represents the natural processes through PROMET and important water related actors as multi-agents. 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

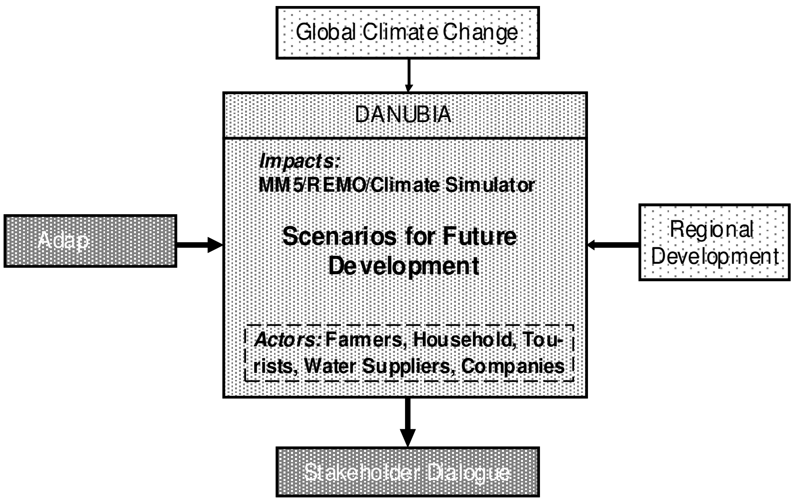


Figure 3. *Schematic diagram of the utilization of the Global Change Decision Support System DANUBIA for the stakeholder dialogue within the GLOWA-Danube project.*

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, which are represented as self-contained multi-agents, 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 sectors. 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 (ministries, environmental agencies, energy sector, etc.). 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 new scenario run. The efficiency and effectiveness of the proposed decision alternatives will then be discussed with the stakeholders in a second iteration.

3. PROMET – The hidrological 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.

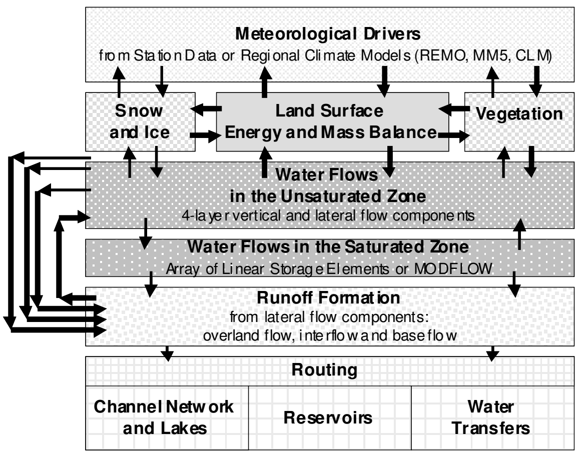


Figure . *Schematic diagram of the compartments of PROMET*

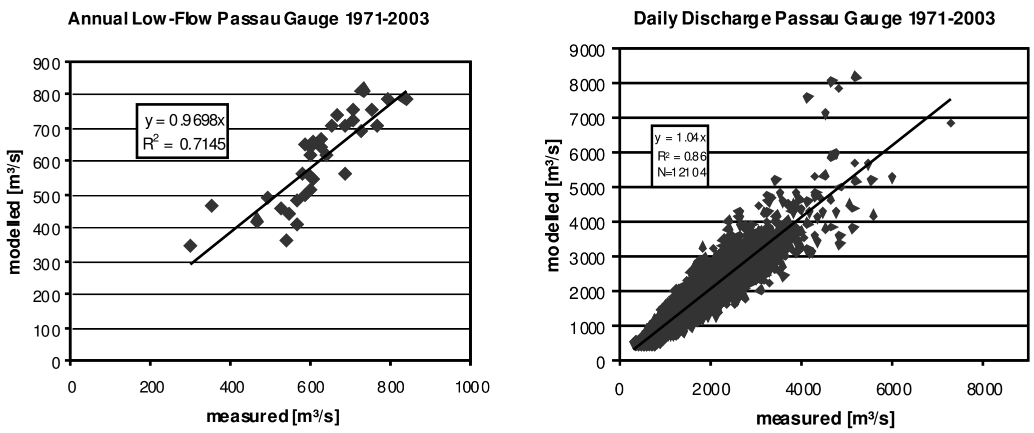
3. PROMET should be spatially explicit in all process descriptions. In order to be most compatible with models from other disciplines (e.g. regional climate models, carbon models, groundwater models, multi-agent raster-based decision models) the spatial representation in PROMET is based on an isotropic grid. A watershed is composed of a set of raster ele-

ments, 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.



a) b)

Figure 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.*

5. Climate impact and water scarcity - Scenario investigations

5.1. The stochastic climate change scenario generator

To analyse the changes in runoff induced by a possible change in climate the period from 2011 to 2060 was modelled using the output of a stochastic climate scenario generator. It is based on the global IPCC-A1B scenario and regionalized through an empirical multiplication factor of 1.7, which considers the regional trends of temperature increase , which already took place in the Upper Danube watershed (see Chap.2.2). This regional adaptation of the IPCC

A1B scenario results in a 3 degree temperature increase in the Upper Danube watershed between 1990 and 2060.

The stochastic climate scenario generator belongs to the family of „nearest-neighbour resampling“ approaches (Yates et al. (2003), Buishand and Brasma (2001), Young (1994), Orlowsky et.al. (2007)). It uses a set of historical measurements from a meteorological station network, which covers the area under consideration as primary data and assumes that the climate of the study area will not change completely. This means that the meteorological situations, which will occur in the selected future time period have already been measured in the past. Future warming or drying will therefore only change the probability with which different meteorological situations will occur.

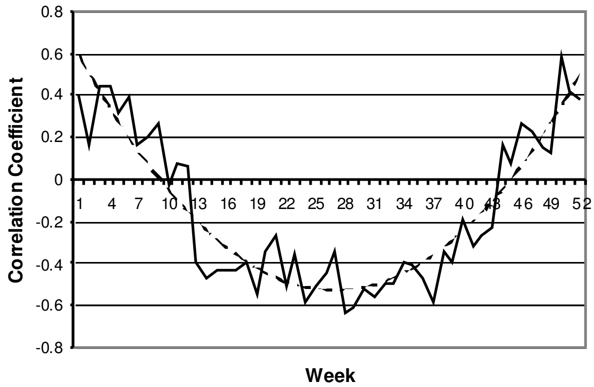


Figure 6. *Correlation coefficient for the weekly relation between temperature and rainfall of the meteorological station measurements (277 stations) in the Upper Danube basin from 1960-2006.*

The historical set of meteorological stations data from the period from 1960-2006 is analysed for the average weekly relation between mean temperature and mean rainfall. The correlation coefficient of the average relation between weekly temperature and rainfall in the Upper Danube is shown in Fig.6 for all 52 weeks. Fig.6 shows, that in the Upper Danube winter rainfall increases with temperature whereas in summer decreases with temperature.

The generation of future time series of meteorological data from past measurements resequences weekly slices of historical station measurements to reflect the assumed trends in future temperature and rainfall development and the natural variability of weather. The generation of a new time series for the period form 2011 to 2060 is accomplished as follows:

1) create the future regional temporal trend in **temperature increase** from the global IPCC SRES-A1B Scenario (see Fig. 2).
2) create the future regional **trend in rainfall** from the regional results of IPCC for Southern Germany (IPCC (2007)). For this region IPCC states that there will be a likely change in DJF winter rainfall amounts of app. +8% and a likely change in JJA summer rainfalls of app. -13% between 1990 and 2090. These seasonal trends were transformed using a spline interpolation into weekly trends shown in Fig. 7.

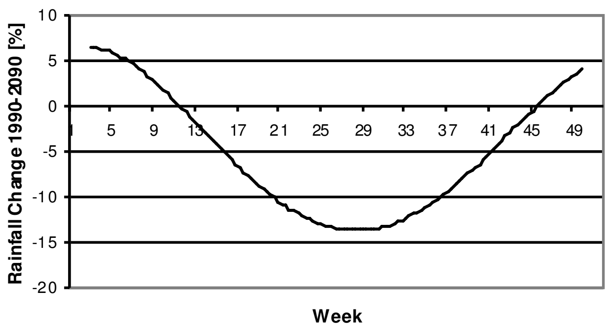


Figure 7. *Expected weekly change in rainfall for Southern Germany according to IPCC (2007).*

3) consider stochastically the short term meteorological variations in the Upper Danube basin using a random number generator. It uses the weekly covariances determined from the historical data set (see Fig. 6).

The stochastic climate change scenario generator compiles the future meteorological data set in weekly slices on the basis of the measured time series of station data from the German and Austrian met-offices using the data from the historical week, which best fits to the determined pair of average temperature and rainfall using the trends and the random number generator.

Table 2. *List of the realisations 1-12 together with the zero-hypothesis that temperature will not change in the future. Column 2 expresses the storyline, columns 3, 4 and 5 give values for total/annual mean rainfall, mean temperature at the 1% percentile and mean annual rainfall for the respective storyline.*

Realisation	Storyline	1% Precip. [mm] ([mm/a])	1% JJA-Temp. [^{o}C]	Annual Rainfall [mm]
0	no temperature change until 2060			1080
1	mean annual rainfall between 2011-2035			1027
2	mean annual rainfall between 2036-2060			922
3	min. rainfall of 5 consecutive years 2011-2035	4015 (803)		
4	min. rainfall of 5 consecutive years 2036-2060	3883 (777)		
5	min. rainfall of 3 consecutive years 2011-2035	2517 (839)		
6	min. rainfall of 3 consecutive years 2036-2060	2387 (796)		
7	min. rainfall of 1 year 2011-2035	791		
8	min. rainfall of 1 year 2036-2060	762		
9	max. JJA temp.of 5 consec. years 2011-2035		20.15	
10	max. JJA temp.of 5 consec. years 2036-2060		20.35	
11	max. JJA temp. 2011-2035		21.62	
12	max. JJA temp. 2036-2060		21.71	

By varying the seed of the random number generator and re-running the described procedure a large number of statistically equivalent but different realisations of the same climate change scenario can be produced in a computationally efficient way. Since the random number generator assumes normal distributions it is possible to even assign a probability (e.g. the 1% percentile) to each realisation of the climate change scenario. In order to evaluate the uncertainty of the estimated change in low-flow an ensemble of the 0-hypothesis, that climate change will stop in 2011 and 12 different realisations of the same IPCC A1B climate scenario was modelled and analysed. The following strategy was applied:

1) The 12 realisations follow different storylines. Each storylines expresses a set of assumptions, which allow to choose one valid realisation from a large number of statistically equivalent realisations of simulated meteorological time series. The storylines are shortly described in column 2 of Tab. 2. Realisation 1 and 2 represent two average storylines by choosing the time series with the most probable average temperature for the first and second time period. Realisations 3-12 represent more extreme storylines by choosing situations of prolonged dryness of 1, 3 and 5 years or extremely warm summer. The criterion for choosing the realisations is the 1%-percentile value.
2) For each storyline 5000 statistically equivalent future meteorological data sets were produced by applying the procedure described above. For each realisation a new seeds was statistically chosen for the random number generator.
3) The 5000 meteorological data sets were analysed and the realisation, which fulfilled the criteria of the selected storyline listed in Tab. 2 was chosen to select the valid future met data sets for the hydrological simulations with PROMET.

5.2. *Effects of climate change scenarios on low-flow*

For all selected scenarios together with the zero-hypothesis in Tab. 2, 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 PROMET. The resulting hourly runoff data was aggregated to daily values for the outlet gauge in Achleiten. The 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. 8. The left part of Fig.8 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.8 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 significant changes in the simulated future annual low-flow.

On the other hand the assumed IPCC A1B scenario leads to a considerable reduction of simulated annual low-flows for all selected storylines of Tab. 2. As can be expected there also is a considerable annual scatter in the future development of low-flow. The scatter within each storyline is of the same order of magnitude as the scatter between the storylines. Nevertheless the general trend of decreasing low-flows is obvious.

Fig. 9 shows the result of an analysis of the course of the 50-years return period low-flow condition at gauge Achleiten. The bold black curves as well as the dashed grey curve represent the evolution of the 50-years return period low-flow under different assumptions. All three 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 ($NM7Q_{50}$).

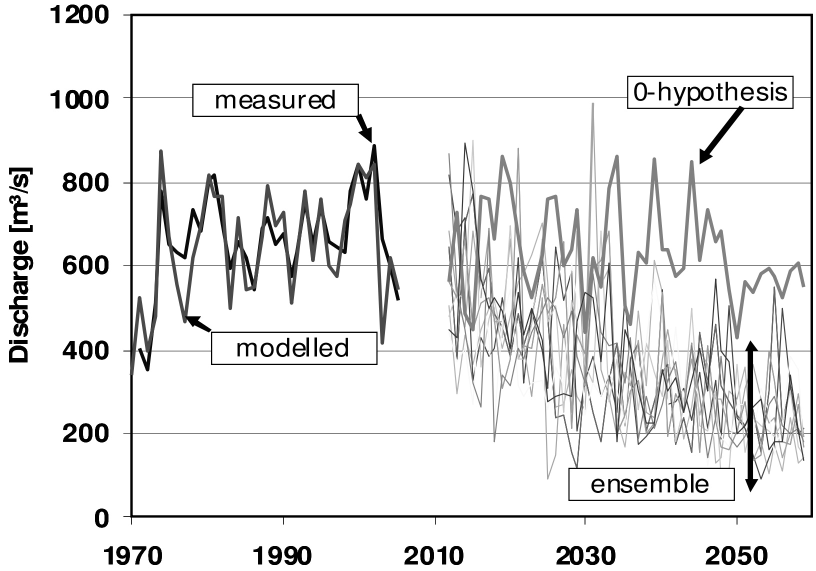


Figure 8. *Annual low-flow NM7Q (min. 7-days mean discharge) at gauge Achleiten for 1970-2005 and 2011-2060 using the 0-hypothesis and the 12 realisations from the stochastic climate change scenario generator as listed in Tab.2.*

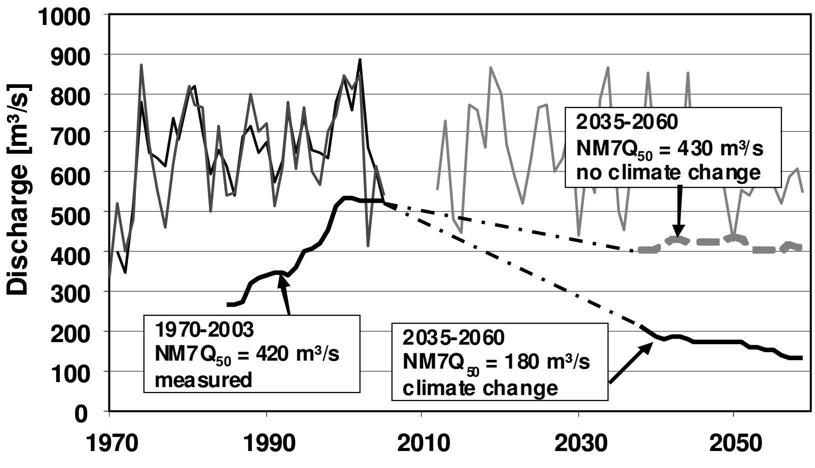


Figure 9. *Evolution of the 50-years return period of te NM7Q low-flow condition at gauge Achleiten averaged from realisations 1-12 from Fig.8.*

The curves in the upper part of Fig. 9 were taken from Fig. 8 and represent the measured and modelled past annual 7-days low-flows as well as the result from the 0-hypothesis. The bold black curve in the right part of Fig. 9 represents the evolution of $NM7Q_{50}$ under climate change conditions. It was produced by averaging the annual low-flows from realisation 1-12 in Tab. 2. As can be seen clearly 1) the average 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) $NM7Q_{50}$ decreases sharply and is reduced to approximately half of its present value by 2030 and to one third of its value by 2060 when assuming the averaged effects of the slected ensemble of realisations of the IPCC A1B climate change scenario. This already indicates a change in the flow regime of the Upper Danube since low-flows with such a low discharge have not yet been measured in the past.

5.3. Effects of climate change scenarios on the hydrologic regime

In a second step the simulated daily discharges from the period from 1960-2060 were aggregated to monthly averages. For the period from 1960-2006 measured meteorological data was used, the period from 2011 to 2060 was simulated using realisation 1 from Tab. 2. The monthly average was then aggregated to decadal means to describe the decadal changes in the hydrologic regime of the Upper Danube. The result of the analysis is shown in Fig.10. Five effects can clearly be distinguished in Fig.10: 1) a discharge maximum during the summer months in the first three decades, 2) the increase in winter runoff between 1960 and 2060. First signs are already evident 1970s, 80s and 90. They clearly amplify after 2010. 3) a sharp decrease of summer runoff starting in the 1990 and accelerating in the 21st century, 4) a decrease of the discharge maximum in spring originating from snow melt from the lower elevations in the Alps and 5) an overall reduction of runoff volume during the period from 1960-2060. Fig. 10 demonstrates that the assumptions of the applied climate change scenario lead to a more or less seamless future change of the runoff regime of the Upper Danube watershed. The historical time series already indicate the change, which will strongly manifest in the middle of the century.

5.4. Effects of climate change scenarios on water stress days

The sharp decrease in river runoff, which is simulated for the Upper Danube for the summer months towards the middle of the century, has its main origin in disappearing glaciers and the reduced snow storage in the Alps. The decreasing summer rainfall together with increasing temperatures and reduced cloud cover also increase evapotranspiration demand and deplete the soil moisture storage. This leads to increased vegetation water stress as can be seen in which results from the analysis of the output of the energy balance submodel of PROMET. For each pixel in the watershed the days with reduced evapotranspiration due to soil moisture deficit were summed up. Fig. 11 shows the water stress days per year averaged over the whole area of the watershed. The number of simulated water stress days slightly increased in the period from 1960 to 2006. As a consequence of the assumed regional climate change the simulated water stress days will almost double until 2060. The increase in water stress days is strongest in the lowlands, where presently intensive rain-fed agriculture is the predominant land use. In order to stabilize agricultural yield in these regions it would be inevitable to introduce intensive irrigation.

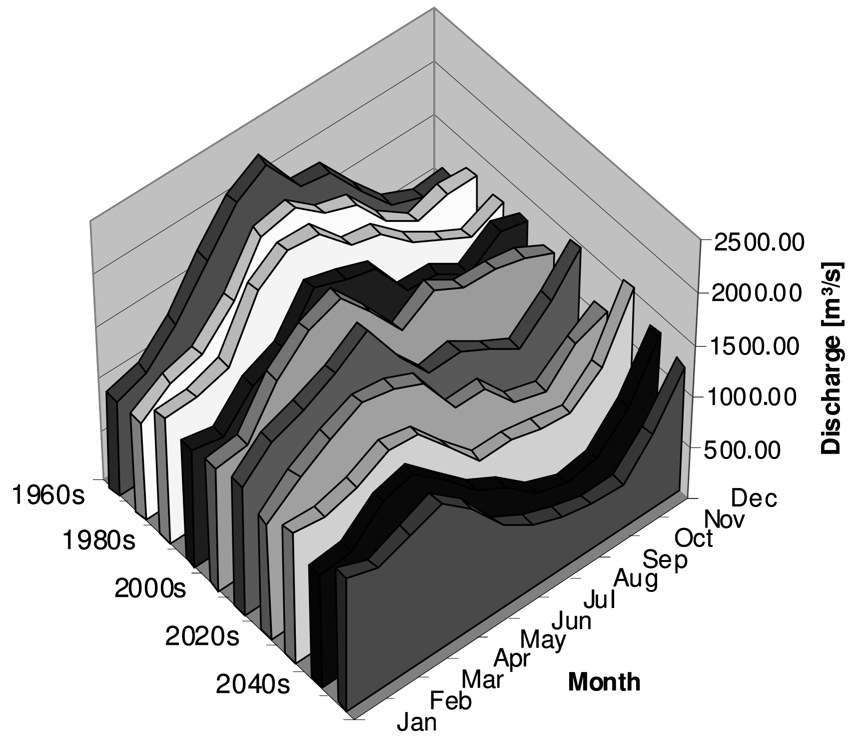


Figure. 10. *Change in the modelled average decadal monthly discharge from the Upper Danube basin based on measured meteorological data (1960-2006) and realisation 1 of Tab. 2.*

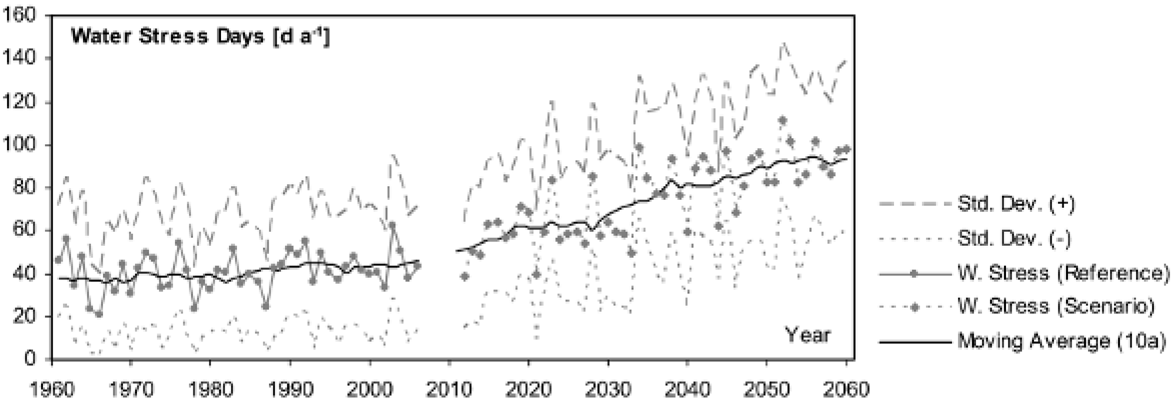


Fig. 11. *Annual water stress days averaged over the Upper Danube watershed for the reference and scenario period using realisation 1 in Tab.2.*

6. Conclusions

According to 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 as well as the runoff regime and water stress days in the Upper Danube river basin severe changes in the runoff regime, evapotransporation and the resulting low-flow conditions in the Upper Danube can be expected during the next 50 years. They rage 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 and a complete change in runoff regime from present summer peak to a future winter peak. The reasons for these severe changes 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 will not be stored in the Alps; 2) the decreasing summer rainfall, 3) the increasing evapotranspiration. All three factors work in the same direction, amplify each others and by the middle of the century result in severe water scarcity in the watershed, which under present climate conditions is not experiencing water scarcity.

It can be expected that the regime change together with the reduction in discharge and the introduction of irrigation will have strong impacts 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. In the future the existing reservoirs will have to change their operation rules in order to fully exploit winter runoffs and augment summer low flows instead of today's winter low flows. Additional reservoirs may have to be built in the Alps to substitute today's natural snow and ice storage.

Acknowledgment

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

Buishand, T.A. and T. Brandsma, 2001: Multisite simulation of daily precipitation and temperature in the Rhine Basin by nearest–neighbour resampling. *Water Resour. Res.*,**37**(11), 2761–2776.

IPCC, 2007: Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: *Regional Climate Projections*. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ludwig, R., M. Probeck, W. Mauser, 2003. Mesoscale water balance modelling in the Upper Danube watershed using sub-scale land cover information derived from NOAA-AVHRR imagery and GIS-techniques. *Physics and Chemistry of the Earth* **28**, 1351-1364.

Mauser, W. and H. Bach, 2008: PROMET – a Physical Hydrological Model to Study the Impact of Climate Change on the Water Flows of Medium Sized Mountain Watersheds. *J. Hydrol.*, (submitted).

Orlowsky, B., F.W. Gerstengarbe and P.C. Werner, 2007. A resampling scheme for regional climate simulations and its performance compares to a dynamical RCM. *Theor. Appl. Climatol.* online published, DOI: 10.1007/s00704-007-0352-y

Yates, D., S. Ganggopadhay, B. Rajagopalan and K. Strzepek, K., 2003. A technique for generating regional climate scenarios using a nearest neighbour algorithm. *Water Resour. Res.*, **39**(7), SWC 7–1 – 7–14.

Young, K.C., 1994: A mulitvariate chain model for simulating climatic parameters with daily data. *J. Appl. Meteor.*, **33**, 661–671.