Climate Change effects on hydropower plants in the Upper Danube watershed

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Abstract Climate Change will have direct impacts on the hydrological cycle and therefore also on the development of hydropower generation. Within the interdisciplinary research project GLOWA-Danube the hydropower generation is modelled with the physically-based, non-calibrated hydrological model PROMET for nearly all bigger, current existing hydropower plants in the Upper Danube watershed. This paper gives an overview of a plausible scenario on the development of the hydropower generation for the next 50 years, considering an IPCC-SRES-A1B based regional climate change scenario. Hydropower generation will decrease on average by approx. -2% in the period 2011-2035 and by approx. -11% in the period 2036-2060. Beyond this general trend, regional differences were also identified.

Key words Climate Change; hydropower generation; hydrological modelling; PROMET; GLOWA-Danube; Upper Danube watershed

INTRODUCTION

Hydropower is a very important and environmentally friendly energy provider. It comprises one fifth of the world’s electric energy generation following the fossil energy resources carbon, mineral oil and natural gas (Strobl & Zunic, 2006). In Europe for example, hydropower was already used in former times and was extended mainly in the last 50 years, wherefore its today’s potential is considerably explored.

Regions with large runoff and steep elevation rates are generally predestinated for hydropower generation. This energy resource, however, depends largely on the catchment-based water balance and reacts quite sensitive to changes of the water amount and its seasonal cycle. Therefore climate change effects on the hydrological cycle will also have a direct impact on hydropower generation. Diverse studies show a future decline of runoff rates in alpine areas and project this effect also to a reduction of hydropower generation (Rothstein *et al.*, 2008, Kuhn, 2007, Piot, 2005, Vischer & Bader, 1999). On the demand side recent predictions outline a future increase in electric energy consumption, even when taking into account enhancements of efficiency and energy saving techniques. To compensate this predicted increase and due to environmental reasons, renewable resources like hydropower will even become more important in the future. For example, the German Free State of Bavaria plans to enhance today’s hydropower capacity by 10% in building new power plants, and modernizing, reactivating and enlarging older power plants in the next years (E.ON Wasserkraft GmbH & Bayerische Elektrizitätswerke GmbH, 2009). In Bavaria and in the Austrian Province Tyrol feasibility studies for an increase were already carried out. The calculations, on which these studies were based on, however, did not sufficiently take into account climate change effects.

For accurate estimates, it is important to firstly consider the general trend for the current existing hydropower plants and then as a second step to assign this simulated trend also to planned enhancement strategies. Thus, plausible estimates of the entire potential of future hydropower generation can only be made in context with Climate Change. This paper outlines the trend of a scenario for the future situation of hydropower generation under IPCC-SRES-A1B climate change conditions by considering nearly all larger, already existing hydropower plants in the Upper Danube watershed. For this purpuse a specific mudule calculating hydropower generation, based on runoff and the hydraulic head, was devoloped within the hydrological model PROMET.

HYDROPOWER PLANTS IN THE UPPER DANUBE WATERSHED

The interdisciplinary research project GLOWA-Danube (www.glowa-danube.de) explores various physical and social impacts of Global Change on water resources in a regional focus of the mountainous Upper Danube watershed (77000 km^2) (Fig. 1) in Central Europe for the next 50 years. The catchment is mostly characterized by the

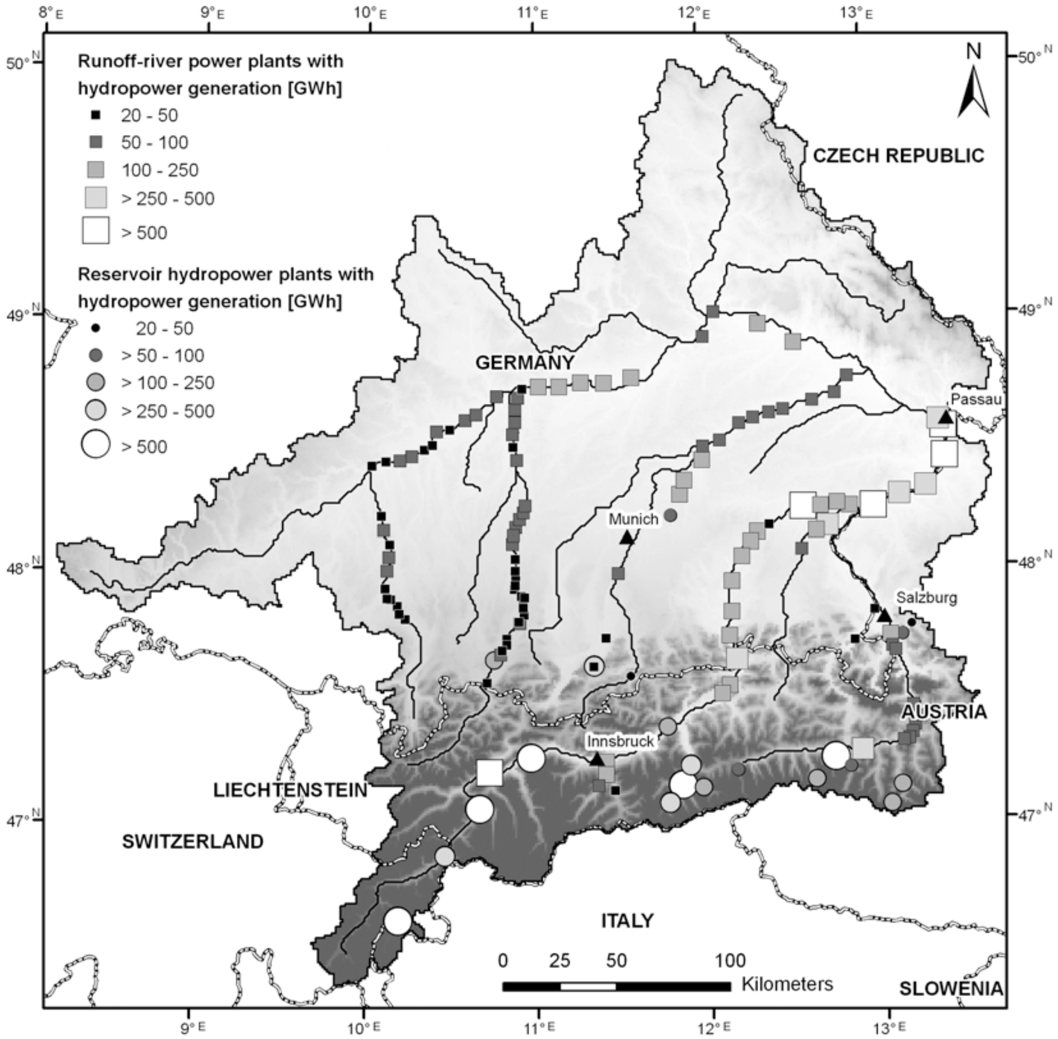

Fig. 1 Upper Danube watershed with main rivers and hydropower plants.

Alps and the alpine valleys in the southern part, the alpine forelands in the middle and the Danube lowlands and the mid-altitude mountains of the Bavarian Forest and the

Swabian Alb in the northern part. The catchment is mostly characterized by its alpine topography with steep elevation gradients, particularly in the Alps. The altitudes range from up to 4049 m a.s.l at Piz Bernina in the Alps to 287 m a.s.l at the discharge gauge Achleiten. The meteorological gradients for the mean annual temperature vary from -4.7 to +9°C and for the mean annual precipitation from 650 to more than 2000 mm. The evapotranspiration ranges from 100 to 700 mm per year, the runoff from 150 to 1750 mm per year (Mauser & Bach, 2009). Though, the river Danube is mostly fed by the alpine headwaters of the river Inn. The alpine runoff regime is highly influenced by the snow and glacier storage of the Alps (Weber *et al.*, 2009; Prasch *et al.*, 2008; Baumgartner *et al.*, 1983). Besides these physical gradients, the heteorogenous research area also shows strong gradients in social factors and processes. Water resources are intensively used by agriculture, tourism, industry and energy providers.

Because of its high runoff rates and steep elevation gradients, the Upper Danube watershed is ideally suited for hydropower generation. In the German Free State of Bavaria, covering the largest part of the research area, hydropower generation for electrical demand amounts to 15 to 18% (Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie, 2008). In the Austrian province Tyrol, which covers about 14% of the catchment, even 75% of electricity demand is generated by hydropower (Amt der Tiroler Landesregierung, 2008). In the reseach area approx. 120 runoff-river power plants with a range of annual hydropower generation of 20 to 500 GWh are modelled. They are mainly situated on the river Danube and its larger tributaries Iller, Lech, Isar, Inn and Salzach. Because of the high runoff rates, the biggest runoff-river plants are situated at the highly alpine influenced river Inn. In the alpine headwaters approx. 20 big reservoir hydropower plants are installed and modelled, mostly with a high annual hydropower generation of more than 250 GWh (GLOWA-Danube Projekt, 2010 (chapter 1.19)).

In order to increase the efficiency of the natural energy resource water, for each reservoir individual monthly-based operating rules control the water discharge from the reservoir depending on hydro electrical demands. In total, the model-implemented hydropower generation of the runoff-river power plants amounts to approx. 13 TWh and of the reservoir hydropower plants to approx. 6 TWh. Fig. 1 shows all hydropower plants included in the model.

MODELLING OF HYDROPOWER PLANTS WITH PROMET

The simulation of hydropower generation is integrated in the physically-based, non-calibrated hydrological model PROMET (Processes of Radiation, Mass and Energy Transfer) (Mauser & Schädlich, 1998; Mauser & Bach, 2009). The model is fully spatially distributed, raster-based with raster elements of 1 km². It strictly follows the principle of conserving mass and energy fluxes and runs on an hourly time step. All meteorological and land surface components, including land-atmosphere energy and mass exchange, snow and ice accumulation and ablation, vertical and lateral unsaturated and saturated flows, channel flows and flows throuh lakes, man-made reservoirs and water transfers, are fully coupled.

Nearly all of the current existing hydropower plants with a maximum capacity of more than 5 MW are implemented in PROMET to simulate the hydropower generation with a temporal resolution of one hour. The investigation includes approx. 140 hydropower plants, shown in Fig. 1, which are all individually parameterized by the mean annual hydropower generation, the hydraulic head, the efficiency factor, the maximum capacity and the comissioning date. For the model simulations of past and future time periods all data are based on the present parameterization of the hydropower plants.

In general, hydropower generation is based on potential and kinetic energy. Besides the efficiency factor η, it depends mostly on the two factors runoff Q and hydraulic head H. The capacity P of each hydropower plant was calculated for each time step by the following equation (Strobl & Zunic, 2006):

$$P = \eta \cdot \rho \cdot Q \cdot g \cdot H \;\; [kW] \tag{1}$$

where η is the efficiency factor of a hydropower plant (%), ρ is the density of water (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), Q is the runoff (m^3 s^{-1}) and H is the hydraulic head (m). For further analysis the data were aggregated to annual values of hydropower generation.

To generate the capacity for each time step in PROMET, the runoff outputs and the present parameterization of the hydropower plants were simulated. Fig. 2 shows the simulated relationship of capacity and runoff for runoff-river power plants and reservoir hydropower plants. The simulated energy generation starts at a minimum runoff value Q_{min}, which mainly is based on low flow and residual flow restrictions. An increase in runoff leads to an increase of the capacity until the maximum capacity P_{max} at an optimal runoff Q_{opt} value is reached. For most hydropower plants this is also the maximum discharge of the turbines. For runoff-river power plants it is assumed that after achieving P_{max} the capacity will decrease by more runoff in the river because of a reduction of the hydraulic head by a rising downstream water level. The capacity will decline until a set Q_{max} value. This point occurs e.g. by extreme flood events. The simulated relationship of capacity and runoff for reservoir hydropower plants handled quite similar. After reaching Q_{opt}, P_{max} is hold for a longer time constantly, because rising downstream water levels have less influence. In general, hydropower is reduced when low flow and flood events emerge. The simulated capacity model output for each time step was then aggregated to annual hydropower generation values.

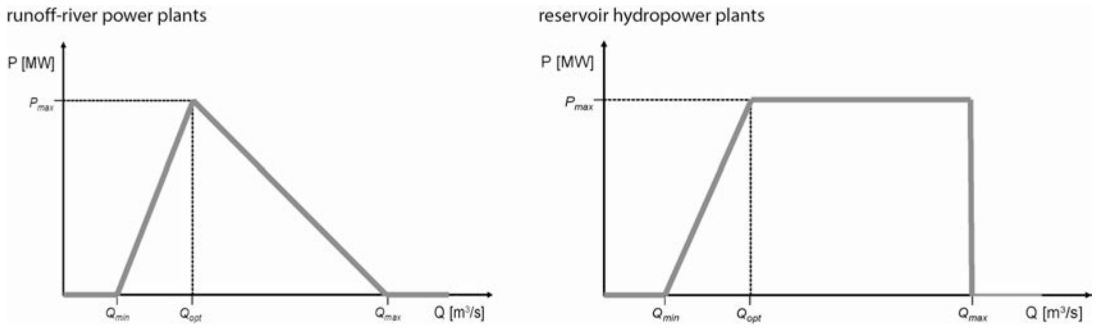

Fig. 2 Simulated relationship of capacity and runoff for runoff-river power plants (left) and reservoir hydropower plants (right).

Furthermore, each reservoir power plant has monthly-based standard operating rules to control the storage and runoff, depending on hydro electrical demands and the water volume stored in the reservoirs. These rules indicate the man-made shifting of the reservoir inflow and outflow in the course of the year. Besides, all bigger water

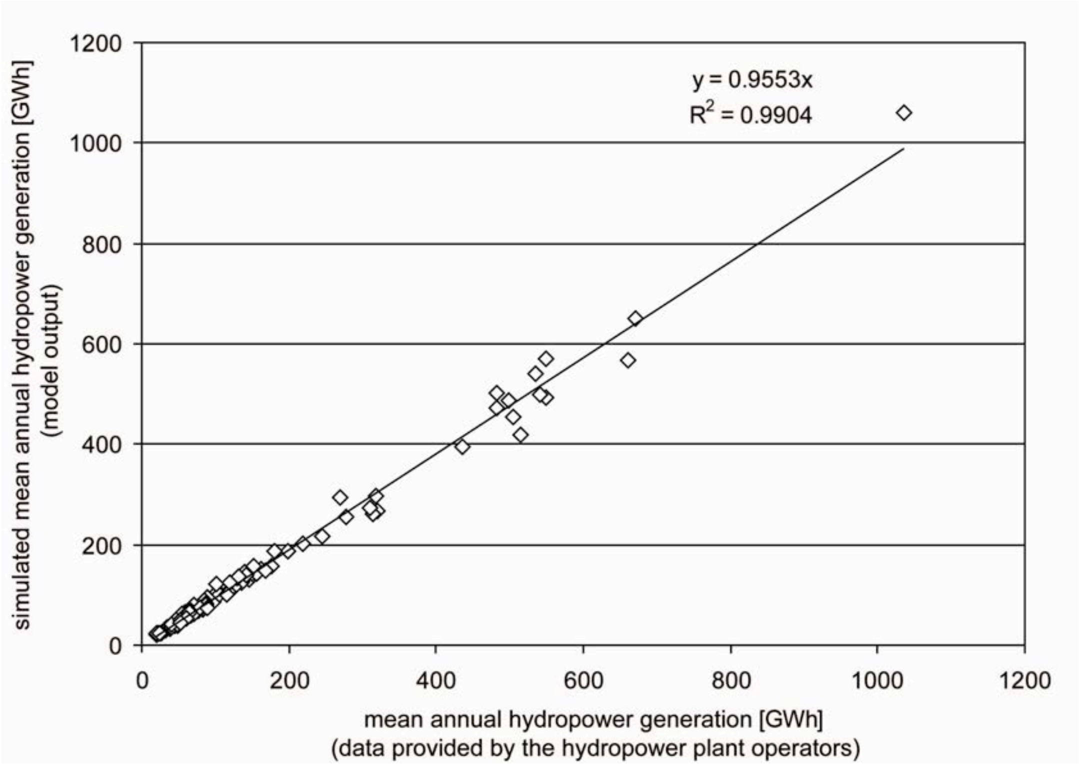

Fig. 3 Validation of the simulated hydropower generation for all simulated hydropower plants in the Upper Danube watershed for the time period 2000-2006.

diversions are included in the model (GLOWA-Danube Projekt, 2010 (chapter 2.7); Mauser & Bach, 2009).

The simulated annual hydropower generation has been validated with the published mean annual data from the power plant operators for each hydropower plant on a long term basis for the time period 2000-2006 with a coefficient of determination of more than 0.9 (Fig. 3).

DEVELOPMENT OF HYDROPOWER GENERATION UNDER CLIMATE CHANGE CONDITIONS

To base this study on a plausible climate development for the next 50 years, the GLOWA-Danube climate scenario *REMO regional – Baseline* was chosen as the meteorological driver for the hydrological model PROMET. This scenario is based on the regional temperature and precipitation trend of the regional climate model REMO (Jacob, 2001; Jacob *et al.* 2008; GLOWA-Danube Projekt, 2010 (chapters S2 & S4)), which in turn is based on the global IPCC-SRES-A1B emission scenario. For the Upper Danube watershed the climate scenario *REMO regional – Baseline* outlines an increase of the mean annual temperature of +5.2 °C and a decrease of the mean annual precipitation of -12.6% regarding the time period 1990-2100 (GLOWA-Danube Projekt, 2010 (chapters S1 & 3.1.1)). The development of precipitation and temperature does not proceed evenly in the course of the year, e.g. the precipitation will mainly increase during winter and decrease in the summer months. The temperature rise causes higher annual evapotranspiration and a decrease of annual runoff. Besides, the amount of snow precipitation compared with the total amount of precipitation will decline markedly (Prasch *et al.*, 2008). This will further implicate changes for the runoff regime and the hydropower generation of the Upper Danube watershed.

Fig. 4 shows the percentual value per year of hydropower generation of a 100-year time period from 1961 to 2060 for the average development of all hydropower plants in the Upper Danube watershed. The percentage range is based on the ratio of the simulated annual hydropower generation versus the simulated mean hydropower generation for the past period (1961-2006). The hydropower generation of the years 2011-2060 were simulated with the climate scenario *REMO regional – Baseline*. A decline especially in the second part of the future simulation is clearly visilbe under the chosen regional climate scenario. For this reason, the future development was devided into two periods for the following analysis. The first one considers the years 2011-2035, the second one the years 2036-2060. The average decrease in hydropower generation for the whole Upper Danube watershed for the next 25 years amounts to approx. -2% and for the years 2036-2060 to approx. -11% compared with the reference period 1971-2000. The reason for this relatively sharp effect might be that for the climate scenario *REMO regional – Baseline*, temperature increase starts to accelerate at the beginning of the second period (GLOWA-Danube Projekt, 2010 (chapter S2)).

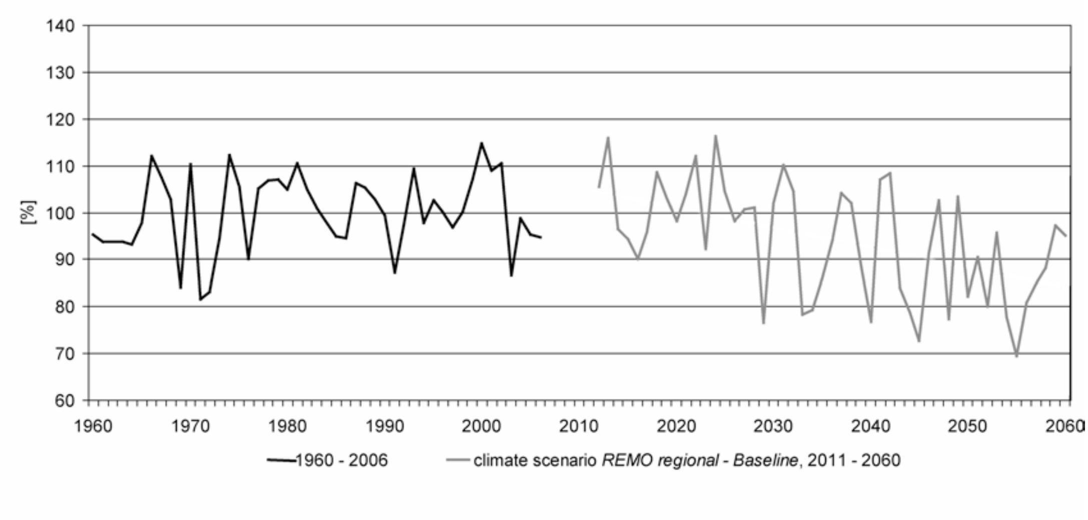

Fig. 4 Development of the hydropower generation in the Upper Danube watershed for the past time period 1960-2006 and the future time period 2011-2060 under the climate scenario *REMO regional – Baseline*.

Besides regarding the development for the whole Upper Danube watershed, it is also interesting to focus on sub-regional impacts. Figs. 5 and 6 illustrate the generally trend of reduction for the simulated future hydropower generation accumulated in six sub-catchments of the Upper Danube watershed for the two future time periods 2011-2035 and 2036-2060 compared with the reference period 1971-2000. The regional trends indicate the development of all hydropower plants for each sub-catchment of the rivers Iller, Lech, Isar, Inn and Salzach as well as for the remaining Danube sub-catchment. In the first time period, the decrease of the simulated hydropower generation in the six sub-catchments ranges between -1 and -4% (Fig. 4) and in the second time period between -8 and -16% (Fig. 5).

The hydropower generation does not decline with the same intensity for all sub-catchments. In both future time periods certain spatial pattern can be identified. Regarding the second time period 2036-2060 (Fig. 6), the decline of the simulated hydropower generation in the highly alpine influenced sub-catchments Inn and Salzach ranges between -8 and -10%. Their runoff regimes are influenced mainly by the snow and glacier ice storage. The runoff regime of the rivers Lech and Isar are characterized by the Northern Alps and the alpine forelands. They show a decrease of about -9 to -12%. The runoff regimes of the sub-catchments Iller and Danube indicate less snow precipitation in the alpine forelands and the Danube lowlands compared to the more mountainous regions of Inn and Salzach. The decrease of the projected hydropower generation ranges between -13 and -16%. Mainly because of changes in the snow and glacier storage, the hydropower generation develops differently in those six sub-catchments. Summing up, the decrease in the southern, alpine sub-catchments is not as distinctive as in the alpine forelands and the Danube lowlands.

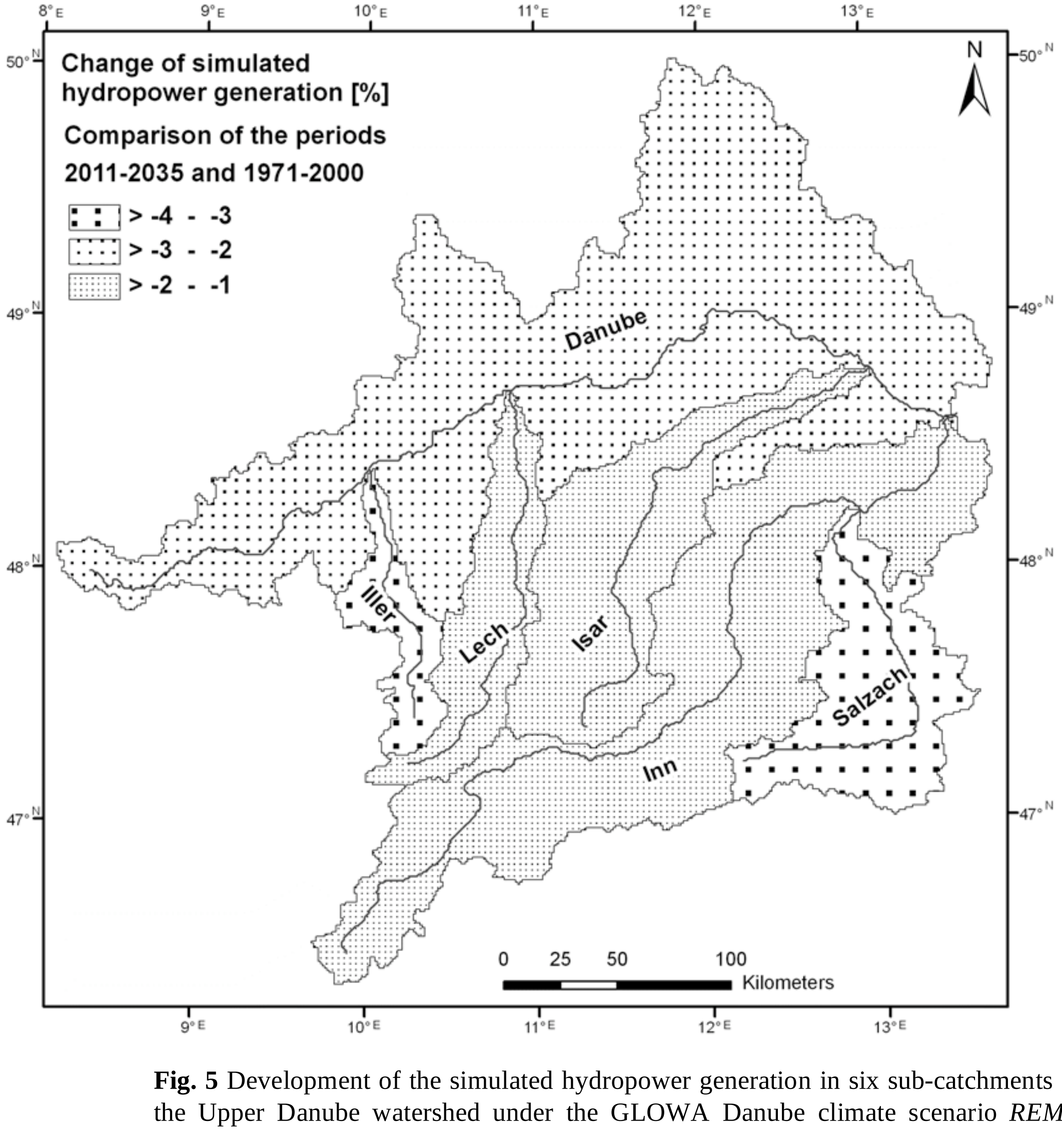

Fig. 5 Development of the simulated hydropower generation in six sub-catchments of the Upper Danube watershed under the GLOWA Danube climate scenario *REMO regional – Baseline* comparing the time period 2011-2035 with the reference time period 1971-2000.

In general, the development of hydropower generation is strongly connected with the runoff development, but the two trends are not completely synchronous. Hydropower generation is, as already said, limited during extreme events like flood or low flow. As a result of Climate Change, the runoff regime in the Upper Danube catchment will also change. In the past, high summer flows, due to melting snow and ice and low winter water levels due to freezing were characteristic. Especially in the alpine headwaters, the future runoff regime will become more balanced. Under the GLOWA Danube climate scenario *REMO regional – Baseline* the low flow situation in winter and in the early spring time will slightly relax, because more rainfall instead of snow precipitation and an earlier melt out of the snow storage will occur (GLOWA-Danube Projekt, 2010 (chapter 3.1.2)). This also causes a runoff reduction in the summer months because of less summer precipitation and an earlier snow and glacier melt phase (GLOWA-Danube Projekt, 2010 (chapters 3.1.4, 3.1.5 & 3.1.8)). Fewer situations of low flow and a more balanced regime in the future will therefore slightly buffer the loss of hydropower generation in the alpine areas. In conclusion, in the higher mountainous areas the decline of hydropower generation will not be as extreme as the decrease of runoff. In contrast the decrease of these two values will be quite similar in the lower parts of the Upper Danube watershed. However, the reduction of hydropower production in all sub-catchments will be quite significant and will especially show a drastic trend in the second future time period 2036-2060.

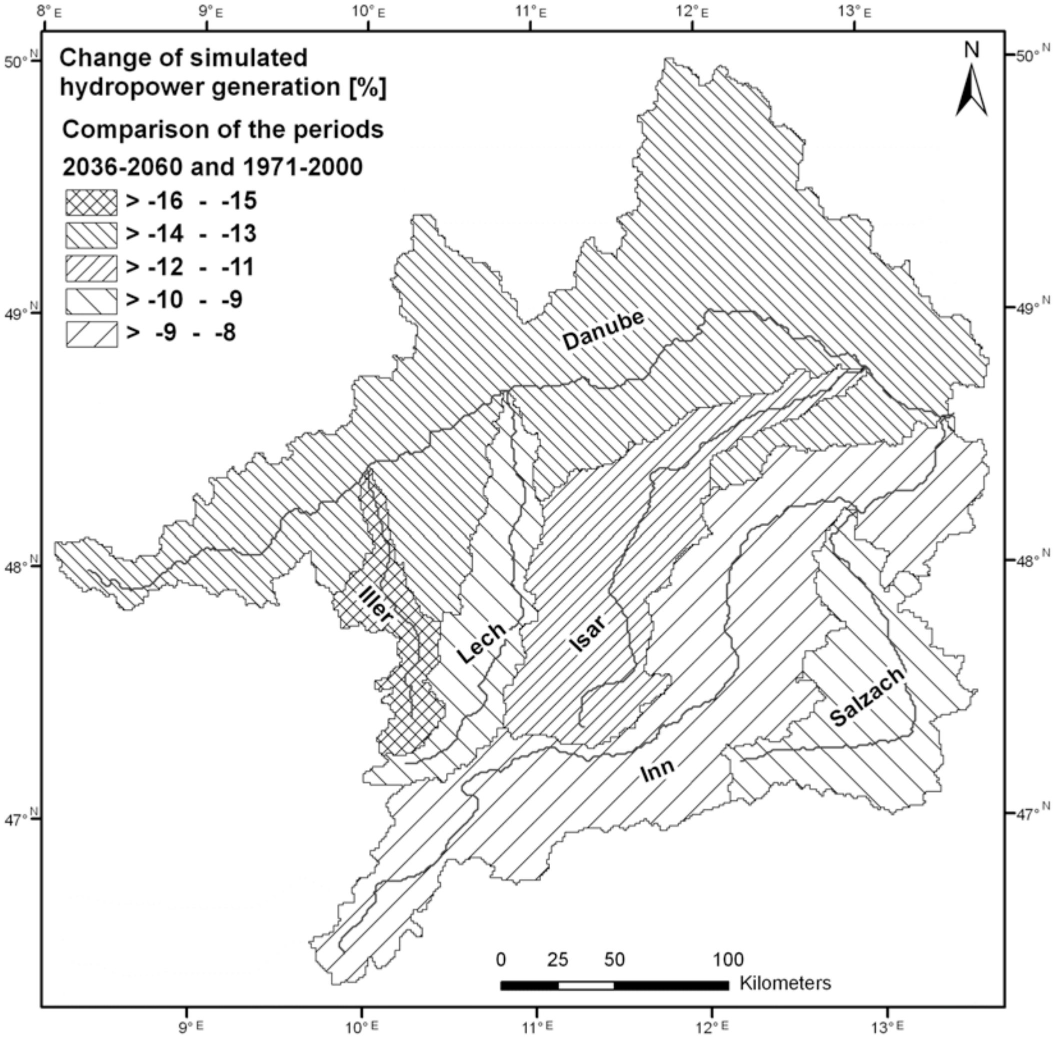

Fig. 6 Development of the simulated hydropower generation in six sub-catchments of the Upper Danube watershed under the GLOWA Danube climate scenario *REMO regional – Baseline* comparing the time period 2036-2060 with the reference time period 1971-2000.

CONCLUSIONS

In reference to the GLOWA-Danube climate scenario *REMO regional – Baseline*, the hydropower generation in the Upper Danube watershed will decrease quite significantly until 2060. Considering regional differences, the decline in the alpine head watersheds will be less than in the alpine forelands and the Danube lowlands because of the buffering factor of the snow and glacier storage and less low flow events.

The projected loss of hydropower generation as a consequence of regional Climate Change could theoretically be compensated through different combinations of measures like extension and the improvement of existing facilities or the construction of new hydropower plants. For the future discussion and decision making processes on the development of hydropower in the Alps and the future role of hydropower as part of the European renewable energy mix, it seems particularly important to take into account climate change effects more thoroughly and to examine a broader range of climate change scenarios to better deal with the uncertainties in the current knowledge of Climate Change especially on the regional scale.

Acknowledgements The authors thank the German Federal Ministry of Education and Research (bmb+f) and the Free State of Bavaria for funding the project GLOWA-Danube. The provision of meteorological and hydrological data by the German Weather Service (DWD), the Austrian Weather Service (ZAMG) and the Environmental Agency of the Free State of Bavaria (LfU) is gratefully acknowledged.

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