Physically based Modelling of Climate Change Impact on Snow Cover Dynamics in Alpine Regions using a Stochastic Weather Generator

Mauser, W. [1], Prasch, M. [1] and Strasser, U. [1]

[1] Department of Geography, Ludwig-Maximilians University, Munich, Germany
Email: w.mauser@iggf.geo.uni-muenchen.de

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EXTENDED ABSTRACT

Alpine mountains are of global importance in providing downstream freshwater, much of it stored as snow several months of the year. This function of a temporal storage of precipitation and its delayed release during melt is one of the key characteristics of a mountain snow cover. In a changing climate, the latter process is supposed to be modified in its temporal dynamics. This important objective is investigated in the frameworks of the projects Brahmatwinn (http://www.brahmatwinn.uni-jena.de) as well as GLOWA Danube (www.glowa-danube.de) by determining the impact of future climate change on the hydrology of the Upper Danube catchment with its alpine headwaters.

For a distributed simulation of the snow cover evolution for both present as well as for future scenarios we apply the model PROMET (**Pro**cesses of Radiation, **M**ass and **E**nergy **T**ransfer), the land surface core of the model framework DANUBIA. In its current version it is a distributed, physical, non-calibrated regional Earth System model, which simulates all water fluxes (rainfall, soil water movement, evapotranspiration, direct runoff, interflow, streamflow) on a 1 km grid base. It also includes a dynamic vegetation model. PROMET has interfaces to the outputs of regional climate models as well as to the groundwater model MODFLOW. It also includes a snow module for simulating the energy balance, the water equivalent and the melt rate of a snow cover.

To validate the modelled snow water equivalent at both the local as well as at the regional scale, two representative weather stations with distinct characteristics in the Upper Danube catchment are chosen, and model results are compared with measurements. Furthermore, we compare distributed simulation results of snow coverage with NOAA AVHRR satellite data derived snow cover.

In a next step, a stochastic, nearest neighbour weather generator to produce climate change scenario data is introduced. It generates a consistent future climate data set for the period 2005-2104 by appropriate stochastic rearrangement of historically measured meteorological data. This data set is then used as input to PROMET to determine the impact of future climate change according to the IPCC-B2 scenario with a temperature increase of 2.7K per 100 years. The impacts of the simulated future climate are discussed focussing on changed precipitation.

Then, the change in snow water equivalent compared to the past 30 years from 1971 to 2000 is analysed for the future periods 2031 to 2060 and 2071 to 2100. For this purpose the mean evolution of the snow cover over the entire period, as well as the annual courses are considered. The duration of the snow cover for the winter season of the respective periods is analysed as well. Finally, the impact of climate change on the snow cover dynamics and its consequences for runoff generation is discussed.

The model is currently adapted to the Upper Brahmaputra basin. In the future, we intend to apply it with properly downscaled output of global circulation models (GCMs).

1. INTRODUCTION

In alpine regions a significant portion of precipitation is stored as snow several months of the year and later released as snowmelt. This function of a temporal storage is an important component of water supply for the downstream population of large mountain-foreland river systems. Due to climate change and population development, the availability of water for humans, plants and animals will be one of the most essential issues for the future (IPCC 2001, IUCN 2003, Barnett et al. 2005). The integrative research projects GLOWA-Danube (Mauser and Ludwig 2002; Ludwig et al. 2003a) and Brahmatwinn (www.brahmatwinn.uni-jena.de) focus on the regional hydrological modelling and determination of the impact of future climate change on the water balance. An important factor for simulating the availability and distribution of water in the test sites of the Upper Danube and the Upper Brahmaputra catchments is the amount, the spatial variability and temporal changes of the snow cover due to the alpine character of the headwatersheds. In this paper, we describe the application and validation of the physical regional Earth System model PROMET in the Upper Danube catchment. As an alternative to GCM output, which is difficult to downscale to the scale considered, we use a network of meteorological stations as inputs for validation and a stochastic, nearest neighbour weather generator to produce physically consistent future climate data sets to be used with PROMET.

2. THE TEST SITE

PROMET is applied to the Upper Danube catchment with an area of 76.653km², covering parts of Southern Germany, Austria, Switzerland and Italy (Figure 1). The test site 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 is characterized by strong meteorological gradients with annual precipitation from 650 to 2000 mm, an annual mean temperature from -4.8 to 9°C, evaporation from 250 to 550 mm per year and annual discharge from 150 to 1750 mm. These physio-geographic attributes are reflected by a high spatial variability in the land use and land cover pattern: forestry and agricultural use are dominant; however, in parts of the catchment the agricultural use is limited due to climatic conditions (Ludwig et al. 2003b). For the simulations presented here, the model PROMET is applied using a temporal resolution of one hour and a spatial resolution of one kilometer.

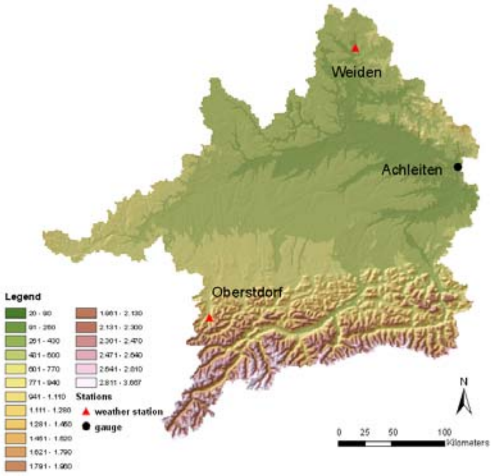

Figure 1. The Upper Danube river catchment with the gauge Achleiten and the weather stations Oberstdorf and Weiden.

3. THE MODEL

3.1. PROMET

PROMET (Processes of Radiation, Mass and Energy Transfer), which is derived from Mauser et al. (1998) is used to model the fluxes energy and matter on the land surface. It considers as well the main runoff components and the snow cover dynamics. In the past PROMET has been applied at different scales from the single field (1 ha) over a microscale region (100 km²) to a mesoscale catchment (100.000 km²) as well as for numerous locations and climatic conditions in a variety of studies (Strasser and Mauser 2001, Ludwig and Mauser 2000, Ludwig et al. 2003b). The concept of PROMET is based on fundamental physical principles like the conservation of mass (water, carbon) and energy. No calibration of model parameters is used to fit the outputs of PROMET to measured data. PROMET consists of the following six interacting modules:

(a) the meteorology module, which interpolates the driving meteorological fields based on topography and determines the radiation balance according to its geographical location, sun angle and cloud cover,

(b) the 4-layer soil hydraulic module calculates the soil water content as a function of infiltration, exfiltration, percolation and capillary rise (Eagleson 1978) as well as the vertical and lateral flows in the unsaturated soil,

(c) the plant physiological module calculates the water transports and carbon allocations in plants as a function of the specific stomatal resistance, determined by absorbed photosynthetic active radiation, temperature, humidity and soil moisture (Baldocchi et al. 1987, Farquhar 1980),

(d) the hydraulics module, which simulates the concentration of the lateral water flows into river runoff following topography and routs the river runoff through the channel network

(e) the aerodynamic module calculates the removal of transpired water vapour into the atmosphere (Monteith 1978), and

(f) the snow module, which is briefly described in the following. It simulates the energy balance, the water equivalent and the melt rate of a snow cover: after the decision whether possible precipitation is solid or liquid according to a threshold wet bulb temperature (if not detected automatically), it is distinguished between potential melting conditions (air temperature $\geq$ 273.16 K) and no melt (air temperature < 273.16 K) for each hourly time step. In the first case, a snow surface temperature of 273.16 K is assumed and melt can occur. Melting snow as well as rainfall first fills the liquid water storage of the snowpack, assumed to be represented by a homogeneous, fractional volume inside the snowpack. Snowmelt is only released from the snowpack if the liquid water storage is filled (Prasch et al. 2007). If the air temperature is lower than 273.16 K, an iterative procedure to adopt the snow surface temperature for closing the energy balance is applied, taking into account the short- and longwave radiation, the sensible and latent heat fluxes, the energy conducted by solid or liquid precipitation as well as condensation/ sublimation and a constant soil heat flux. A detailed description of the model algorithms is given in Strasser et al. (2007a and b).

Input Data

To run PROMET, input data fields of topography, land use and land cover, soil texture and meteorology are required as raster fields. Slope and aspect as well as the hydraulic network are deduced from the digital elevation model. Detailed information of soil physics, e.g. pore size distribution or hydraulic conductivity are taken from literature. Since the version of PROMET, which is used for this study, does not simulate dynamic vegetation growth, dynamic vegetation parameters like leaf area index or canopy height are derived from literature and/or field campaigns. For providing the meteorological input data fields of air temperature, precipitation, wind speed, relative humidity and cloudiness, point measurements at 377 stations of the German Weather Service (DWD) network are interpolated: the three daily recordings at 7 a.m., 2 p.m. and 9 p.m. ("Mannheimer Stunden") are temporally interpolated to hourly values using a cubic spline function. Precipitation is classified in short events (one single recording) and long-term events (two or more consecutive recordings). In the first case, a Gaussian distribution of the precipitation is assumed, whereas in the second case, it is equally distributed in time. For the spatially interpolation of the meteorological parameters for each hour a linear regression between the measured values and the station altitudes, which gives the most likely elevation dependent value of the meteorological variables is superposed with the spatially interpolated residuals of the regression using an inverse-distance-weight approach. This ensures the reproduction of the station recordings and at the same time considers the relief gradient of the parameters (Strasser and Mauser 2001).

Output Data

The results of PROMET consist of both a specified set of output variables for selectable raster elements, and of spatially distributed fields for the catchment area, describing e.g. the evolution and carbon allocation of plants and the water balance and runoff components as well as the actual snow water equivalent or melt rates.

3.2. Validation of Model Results

In this application of PROMET we focus on snow dynamics. The modelled snow water equivalent is validated at representative weather stations with different physiogeographic characteristics, whereas the modelled, distributed snow cover of a particular date is compared with a corresponding snow cover map derived from satellite data.

Validation of Snow Cover Dynamics

For the validation at the point scale, two stations in the Upper Danube catchment with very different geographic conditions are chosen (Figure 1). The validations of the snow water equivalent simulated with PROMET at additional stations can be found in Prasch et al. (2007). Weiden is located in Northern Bavaria in the Waldnaab valley (438 m a.s.l.) and stands for winters with frequent alterations between melting and accumulation periods in winter, whereas the station Oberstdorf (810m a.s.l.), located in Southern Bavaria close to the Alps, represents winters with a continuous snow cover from December to the end of April.

Figure 2 shows the modelled evolution of the snow cover at Weiden and Oberstdorf for the winter season 2003/04, representing a season with little snowfalls, and the results for the extraordinary snowy winter season 2005/06. The measured snow water equivalent of the German Weather Service (DWD) for these periods also is displayed. The analysis of the modelled to the observed values results in a Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970) between 0.94 (1970/71) and 0.85 (2005/06) for Oberstdorf, and 0.92 (1970/01) and 0.81 (2005/06) for Weiden.

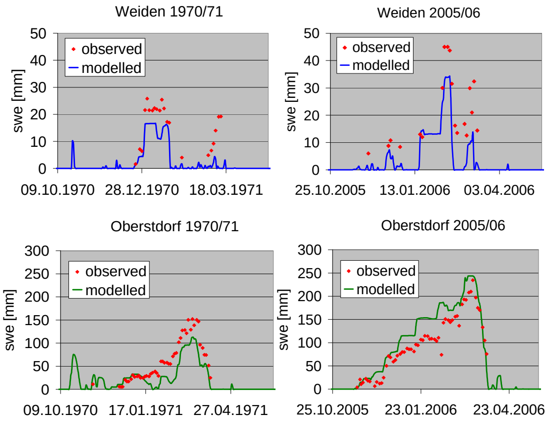

Figure 2. Evolution of snow water equivalent for the weather stations Weiden and Oberstdorf in the winter seasons 2003/04 and 2005/06.

The modelled spatially distributed snow cover for the Upper Danube catchment is validated with satellite derived snow coverage for the winter season 2005/2006. For the validation, images of the medium resolution optical sensor NOAA AVHRR, classified into snow covered and snow free areas are used. Details about the features and processing of these images can be found in Bach et al. (2004) and Appel et al. (2006). Shadow, cloud cover and fog constrain the analysis in parts of the images. Figure 3 shows the spatially distributed model output as well as satellite data derived snow coverage for the Upper Danube catchment for April 7, 2006. 67 % of the catchment area is classified as snow free, PROMET models 65 % as snow free. The spatial distribution is also reproduced by PROMET.

The two independently derived spatial snow cover distributions show great similarities. This successful validation of the snow component of PROMET together with the fact, that PROMET is a physical, non-calibrated model makes it viable to apply it for hydrological simulations using scenarios of the development of future climate.

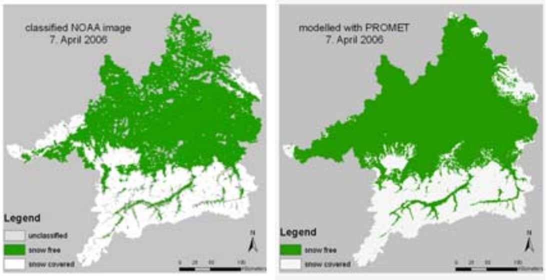

Figure 3. Satellite derived (NOAA AVHRR) and modelled snow coverage for the Upper Danube catchment for the April 7, 2006.

4. STOCHASTIC WEATHER GENERATOR

The stochastic weather generator used herein generates future climate data by a proper rearrangement of historically measured meteorological recordings, originating from the period 1970 to 2003. The results have 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 which are characterized by an average temperature and a precipitation sum. Between these two variables a relationship of the following type is assumed:

$$\overline{P} = f(\overline{T}) \ , \qquad (1)$$

where $\overline{P}$ = monthly precipitation sum and $\overline{T}$ = mean monthly temperature.

First, the measured monthly precipitation and air temperature values are statistically analysed for the period from 1970 to 2003 so that for the considered period twelve mean values of precipitation and air temperature as well as their monthly covariances are available. These parameters represent the intrinsic dependencies between temperature and rainfall for each month in the year. This data forms the basis for a coupled two stage random number generator (IMSL 2003), which uses the monthly means and covariances of temperature and rainfall to determine pairs of interdependent random numbers. 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. The second random number (monthly rainfall) is drawn considering the covariance between temperature and rainfall derived from the past climate time series. 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 with most closely fits the randomly selected pair of mean temperature and precipitation is selected from the historical data using an Euclidian nearest neighbour distance metric (Figure 4).

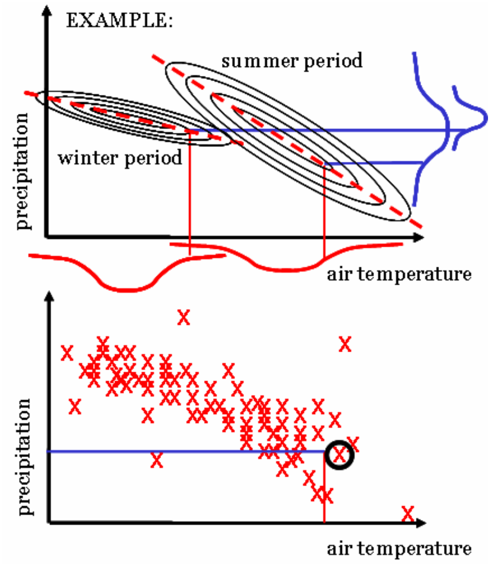

Figure 4. Procedure of the deriving future climate data with the stochastic weather generator

The data of all available stations of this month (air temperature, precipitation, relative humidity, wind speed, radiation and cloudiness) are added to the new meteorological data set. The result of the procedure consists of a 100-year time series of a scenario of possible future meteorological data, which has the same statistical characteristics as the historical data and is characterized by a defined temperature trend and the corresponding rainfall. This weather generator can be classified as a stochastic nearest neighbour resampler, however it produces a likely realisation of future climate and not synthetic weather for regions with sparse data availability like WGEN (Richardson 1981) or LARS-WG (Racso et al. 1991, Semenov et al. 1998) for example.

5. RESULTS AND DISCUSSION

5.1. Scenario of Future Climate

For the period 2005 to 2104 a future climate data set is calculated with the weather generator based on the IPCC scenario B2 which assumes a temperature increase of 2.7 K in the next 100 years (IPCC 2001). The trend is visible in the curves in Figure 5 with the annual variations due to the pseudo-random variations included in the statistical rearrangement of the historical data. The temperature trend, and thereby the precipitation phase change (rain or snow), causes decreasing snow precipitation, though the amount of winter precipitation almost remains unchanged (Figure 5 and 6). In contrast, summer precipitation in June, July and August is reduced by about 1 mm per year from 2005 until 2104. According to the simulated trend in the seasonal precipitation pattern, winter precipitation rises in north-eastern Bavaria as well in the south-east of the catchment, whereas in the central western region winter precipitation decreases. In summer, precipitation decreases almost in the whole catchment, particularly in the south-eastern region (Figure 7).

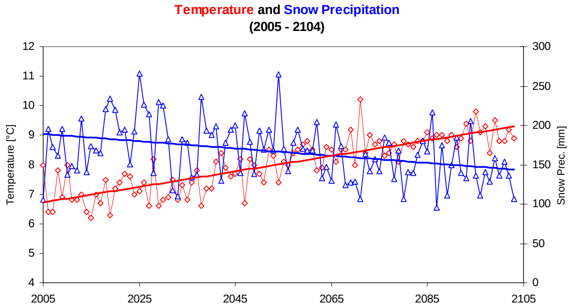

Figure 5. Future temperature and snow precipitation for 2005 to 2105 as simulated with the stochastic weather generator.

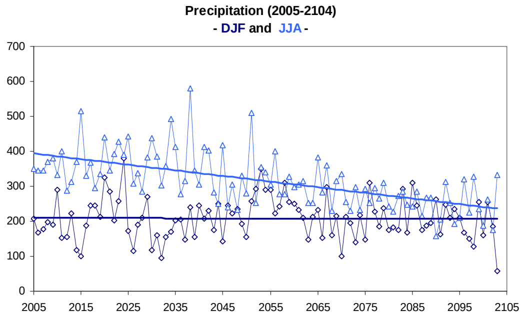

Figure 6. Future winter (December, January, February) and summer (June, July, August) precipitation for 2005 - 2105, as simulated with the stochastic weather generator.

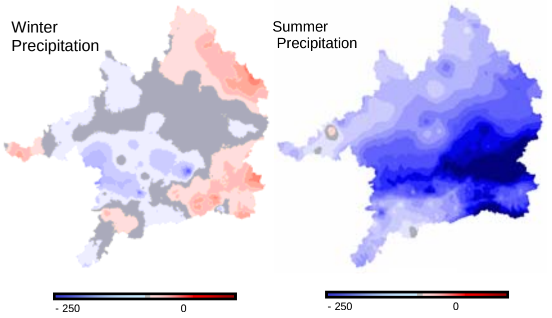

Figure 7. Trend of seasonal precipitation pattern from 2005 to 2105, as simulated with the stochastic weather generator.

The stochastic weather generator enables an efficient provision of future climate scenario data for model applications. The produced meteorological data are within the validated range of PROMET and physically consistent, as they are derived from historical, measured data. Another advantage is the constant spatial resolution of the input data. However, changes in extreme climate characteristics like the dependency between air temperature and rainfall can hardly be considered, and possibilities to consider changes in variability are limited. Any auto-correlation between the periods is also not represented. Nevertheless, the statistical properties of the future climate scenario produced with the stochastic weather generator for the Upper Danube catchment are in correspondence with other regional climate predictions, e.g. from the KLIWA research activities (KLIWA 2006) as well as with the regional climate trend predictions of IPCC (IPCC 2001).

5.2. Future Snow Cover

To analyse the effect of the future climate on the snow cover, mean evolution of the snow water equivalent for the periods of 2031 to 2060 and 2071 to 2100 is compared with the past observations for 1971 to 2000 at the weather stations Weiden and Oberstdorf (Figure 8).

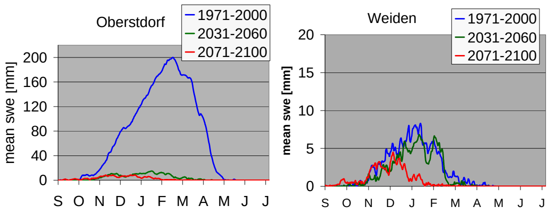

Figure 8. Mean evolution of snow water equivalent for past and future periods for the stations Oberstdorf and Weiden.

In Oberstdorf the simulation shows a strong future decrease of water quantity stored as snow. Furthermore the snow cover melt out is shifted form the end of April to the end of March. In Weiden a similar effect appears in the period of 2071-2100, whereas for 2031-2060 the evolution of the snow water equivalent is just a little behind 1971-2000. As the winter in Weiden today is characterized by a frequent change of rain and snow periods, the effect of the temperature increase is little until the end of the century. Furthermore Weiden is located in a region in the catchment with simulated increasing winter precipitation (Figure 7). In comparing the annual evolution of the snow water equivalent for the three mentioned periods the results are confirmed. Although snow water generally is reduced, the variability in future climate also can cause winters with a snow cover equivalent to the present (Figure 9).

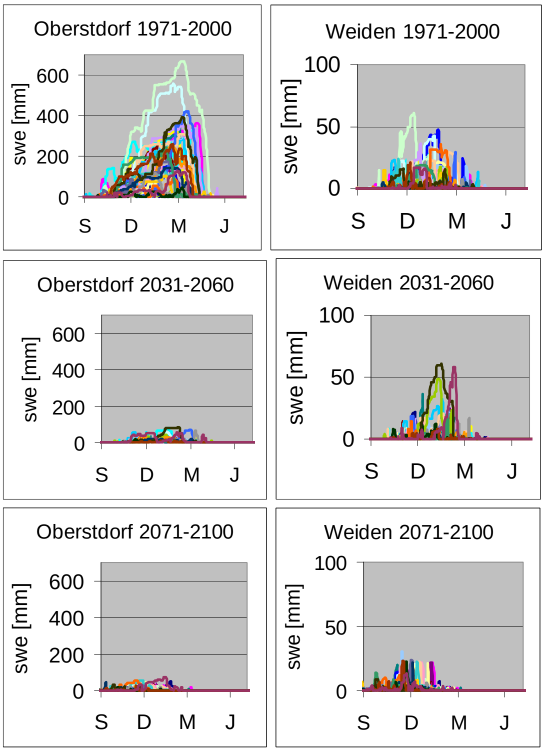

Figure 9. Annual evolution of snow water equivalent for past and future periods for the stations Oberstdorf and Weiden.

The mean duration of the annual snow cover in the past 30 years from 1971 to 2000 varies between 34 days in the Danube valley and 332 days in the high alpine regions of the catchment (Figure 10). Compared to the future annual snow cover from 2031 to 2060, the duration will decrease in the whole catchment. In the higher regions of the Swabian Mountains, the Bavarian Forest and parts of the Alps the decrease lays between 25 and 54 days per year, whereas in the river valleys about 10 days of reduction are modelled (Figure 10). As described above, the effect of temperature increase there is little compared to the mountain forelands and the higher regions.

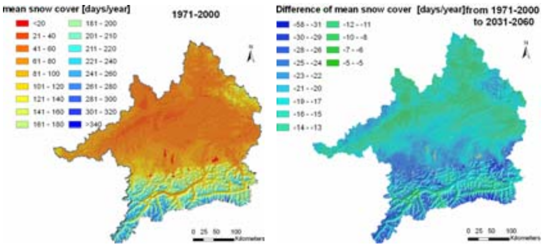

Figure 10. Mean duration of annual snow cover 1970/2000 and trend to 2031/2060.

6. CONCLUSION AND OUTLOOK

The application of the regional Earth system model PROMET in the Upper Danube catchment for the simulation of snow cover variability shows reasonable results for historical data with respect to the validation of the snow water equivalent on the point as well as on the catchment scale. With the stochastic weather generator a future climate scenario is generated rearranging historical meteorological data. This approach enables the simulation of future likely climate change effect on the snow cover evolution. The moderate IPCC-B2 scenario with a temperature increase of 2.7 K per 100 years significantly reduces the quantity of water stored as snow during the winter period. The example of the station Oberstdorf demonstrates, that particularly in Alpine regions of moderate elevation the climate change impact is massive due to the precipitation phase change following the increase in temperature. Furthermore the snow cover duration is reduced compared to the period 1971-2000. Due to reduced amount of water storage and its accelerated release, the changed snow cover dynamics will influence the water availability in the Upper Danube catchment. Nival discharge regimes of tributaries will change to more floods in winter and less runoff during summer.

To investigate the impact of changing snow cover dynamics, the runoff generation will be analysed in detail in its spatial and temporal variation. In addition other scenarios of future climate derived from Global Circulation Models and regional climate models, e.g. CLM or REMO, will be used as input to PROMET in the near future. Within the framework of the Brahmatwinn research project, PROMET will be applied in the Himalayan catchment of the Upper Brahmaputra, and results will be comparatively analysed with those obtained for the Upper Danube.

7. ACKNOWLEDGEMENTS

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