Geogr. Fis. Dinam. Quat.
33 (2010), 221-230, 9 figg.

MARKUS WEBER (*), LUDWIG BRAUN (*), WOLFRAM MAUSER (**) & MONIKA PRASCH (**)

CONTRIBUTION OF RAIN, SNOW- AND ICEMELT IN THE UPPER DANUBE DISCHARGE TODAY AND IN THE FUTURE

ABSTRACT: WEBER M., BRAUN L., MAUSER W. & PRASCH M., *Contribution of rain, snow- and icemelt in the upper Danube discharge today and in the future*. (IT ISSN 0391-9838, 2010).

The hydrological model of the Danubia decision support system allows the sources of runoff to be determined according to glaciermelt, snowmelt and rain at any location of the Upper Danube river network. The analysis shows for the past decade 1991-2000 that in glacierized head watersheds (e.g., Vent gauging station, 35% glacier area) there is about an equal amount of runoff originating from icemelt, snowmelt and rain (about 33% each). Further downstream the portion of icemelt decreases sharply even under present-day conditions with the effect that ultimately 2% of annual runoff is of glacial origin in Passau/Achleiten (basin area of about 77,000 km^2, current glaciation 0.5%), while about ¾ originates from rain and ¼ from snowmelt. This latter fraction is about twice as high as found for subbasins lying exclusively in the lowlands with no connection to the alpine region.

Using the regionally adapted Remo scenario data based on the A1B emission scenario of IPCC, the future development of runoff sources is calculated, taking into account the dynamics of glacierized area reduction using the SURGES glacier model (Subscale Regional Glacier Extension Simulator). In about 30 years, the mean icemelt fraction in the glaciated head watersheds will be less than half of the one observed in the decade from 1991 to 2000. The proportion of snowmelt will be about the same, and rain contribution will increase by 50% to about half of annual specific runoff. After the confluence of the Inn River with the Danube at Passau, the portion from icemelt will be negligible, and 80% of runoff will be from rain and 20% from snowmelt after the year 2030. With the anticipated warming over the whole year and the drying out of the summer season the Alps' capacity to export water will diminish, and water availability will be reduced, mainly through the loss of summer precipitation and increased evaporation, and not so much due to the loss of glaciermelt.

(*) *Commission for Glaciology, Bavarian Academy of Sciences, Munich* - www.glaziologie.de

(**) *Department of Geography, University of Munich* - www.glowa-danube.de

The GLOWA-Danube project was financed by the Federal Ministry of Education and Research, Germany (BMBF), and further financial support was provided by the State of Bavaria as part of the Bavarian Academy Research Programme III.B.1. This research was only possible as an integral part of the GLOWA research initiative, and the contributions of all partners are greatfully acknowledged.

KEY WORDS: Runoff sources, Snowmelt, Glaciermelt, Upper Danube Basin, Inn River, Hydrological modelling, Climate Change.

ZUSAMMENFASSUNG: WEBER M., BRAUN L., MAUSER W. & PRASCH M., *Beiträge des Regens, der Schnee- und der Eisschmelze zum Abfluss im Einzugsgebiet der Oberen Donau in der Gegenwart und der Zukunft*. (IT ISSN 0391-9838, 2010).

Das hydrologische Modell des Entscheidungsunterstützungssystems Danubia ermöglicht für jedes Teileinzugsgebiet im Flussnetz der Oberen Donau die Aufteilung des Abflusses in Komponenten nach der Herkunft von Regen sowie aus der Schmelze von Schnee und Eis. Die Analyse der vergangenen Dekade 1991-2000 ergibt, dass in vergletscherten Kopfeinzugsgebieten (z.B. der Pegel Vent mit einem Gletscherflächenanteil von 35%) der Abfluss zu etwa gleichen Teilen (jeweils 33%) aus dem Regen, der Schmelze von Schnee und von geschmolzenem Gletschereis stammt. Weiter flussabwärts nimmt der Anteil aus der Gletscherschmelze bereits unter gegenwärtigen Verhältnissen sehr deutlich ab, so dass am Pegel Passau/Achleiten (Einzugsgebietsgröße 77.000 km^2 bei gegenwärtig 0.5% Gletscherfläche) nur 2% der jährlichen Abflusssumme von den Gletschern stammen. Drei Viertel liefert dort der Regen und knapp ein Viertel ist geschmolzener Schnee. Allerdings ist der letztere Anteil gut doppelt so hoch wie in Teileinzugsgebieten, die sich vollständig im Flachland ohne Verbindung zum Gebirge befinden.

Unter Verwendung des an die lokalen Verhältnisse angepassten und auf dem Emissionsszenario A1B des IPCC basierenden Remo-Szenario wird die zukünftige Entwicklung der Abflusskomponenten aus den drei Quellen berechnet. Dabei wird die dynamische Veränderung der Gletscherfläche anhand der Berechnungen mit dem Gletschermodell SURGES berücksichtigt. Nach 30 Modelljahren reduziert sich der mittlere Anteil der Eisschmelze in den Kopfeinzugsgebieten auf weniger als die Hälfte während der Dekade 1991-2000. Der Anteil der Schneeschmelze bleibt in etwa konstant, während sich der Regenanteil nahezu verdoppelt und dabei etwa die Hälfte der Jahressumme des Abflusses ausmacht. Nach der Einmündung des Inn bei Passau ist nach dem Jahr 2030 der Beitrag der Gletscher vollständig vernachlässigbar, dort werden zukünftig 80% des Jahresabflusses aus dem Regen und 20% aus der Schneeschmelze resultieren. In Folge einer zu erwartenden

Erwärmung über das ganze Jahr zusammen mit abnehmenden Sommerniederschlägen werden die Exportkapazitäten der Alpen für Wasser abnehmen. Die zukünftig geringere Wasserverfügbarkeit außerhalb der Berge ist hauptsächlich dem Rückgang des Sommerniederschlags und der Zunahme der Verdunstung geschuldet, jedoch kaum der abnehmenden Eisschmelze.

SCHLÜSSELWÖRTER: Abflusskomponenten, Schneeschmelze, Gletscherschmelze, Obere Donau, Inn, Hydrologische Modellierung, Klimawandel.

INTRODUCTION

The Alps are often called the «water towers» of Europe to describe their capacity to export excess water to the adjoining lowlands through the rivers originating in the mountains. Their discharge is more dependable and specific runoff is higher than that of similar-sized lowland basins (Wehren & *alii*, 2010). These advantageous characteristics of the mountain rivers can be summarized as follows:

- Precipitation amounts are higher in the mountains due to orographic enhancement.
- Due to the temperature decrease with height, large amounts of precipitation fall in the form of snow at higher elevations, and the release from this temporary storage in the form of melt occurs preferentially during fair weather periods and thus maintains high runoff values during dry periods in the Spring and early Summer.
- The lower temperature at higher elevations and the presence of snow reduces evaporation and thus favours higher specific runoff.
- Glacier icemelt further enhances water yield from high mountain regions during dry and hot summer periods.
- The steep slopes favour efficient drainage of the water.

Depending on the primary origin of runoff from rain, snowmelt and icemelt a distinction is made between pluvial, nival and glacial regimes. When, under global change conditions, the climate variables of air temperature (energy) and precipitation (mass) change systematically, the components of the water balance also change according to the processes above. As a result, future changes in the local precipitation input will alter specific runoff of a basin accordingly.

The changes will be more pronounced in the Alps as compared to the adjoining lowlands, as the effectiveness of some of the runoff formation relationships mentioned is enhanced due to their primary altitude dependency. While topographic slope will hardly alter due to climate change for example, sustained glacier shrinkage will reduce the amount of icemelt due to the reduction of ice surface. This will have an effect on the seasonal distribution of runoff from glacierized subbasins as well as on water yield as a whole.

A higher proportion of rain to total precipitation will, on the long run, affect runoff formation by producing a higher amount of direct runoff as well as changing the seasonal distribution due to changed volume and duration of snow cover. As the snow cover is present not only over glacierized parts of the head watersheds, but also over the whole alpine terrain, the importance of snow storage on the water balance is obviously very high.

The relative importance of the individual water balance components is also influenced by additional boundary conditions such as the type of vegetation or land use, which determine, for example, storage capacity of the soil or evapotranspiration. Changes in these boundary conditions are difficult to predict and are often an integral part of specific scenarios. They do, however, play a minor role in the mountainous regions in determining runoff as compared to rain, snow- and icemelt. As a result, the changes in the runoff regime due to climate change will be primarily due to changes in these sources of runoff.

PHYSICALLY-BASED MODELLING OF RUNOFF FROM RAIN, SNOW- AND ICEMELT IN MOUNTAINOUS BASINS

The composition of runoff from a large basin according to the origin from rain or the release from snow and ice storage cannot be determined from direct observations of discharge. Up to now, the calculation of these components of runoff formation were achieved only for small head watersheds (see for example Huss & *alii*, 2008; Koboltschnig & *alii*, 2009; Kuhn & *alii*, 2009). For this purpose, a more or less complex snow and glacier runoff model is used, which needed calibration on the basis of measured discharge and glacier mass balance data. When looking at larger size basins with a higher complexity of river networks, the demands on the model strongly increase in respect of the considered processes and data input, and model validation can only be done on the basis of local runoff measurements from subbasins. Ideally, such a model therefore needs to be based on the elementary laws of physics, and the necessary parameterizations of individual chains of processes need to be as universal and static as possible.

A modelling system which considers all important processes was developed within the Glowa-Danube project (Mauser & Ludwig, 2002; www.Glowa-Danube.de). It is called «Danubia» and is an object oriented decision support system, which allows not only the investigation of scientific questions, but which includes also model components for socio-economic processes and their interactions. On the one hand, physical and physiological components describe natural processes such as hydrology, hydro-geology, plant physiology, yield, and glaciology. On the other hand, Danubia uses deep multi-actor models which represent the decisions of the involved actors based on the structure of societies, their framework as well as their interests, for simulation in the considered sectors such as farming, economy, water supply companies, private households and tourism.

Danubia was carefully and successfully validated with comprehensive data sets for the years 1970-2005 and is now available in the third stage of the project for common use by project researchers and stakeholders. Danubia will be made available as «Open Source» at the end of the third project stage in 2010 and will particularly serve decision makers from policy, economy, and administrations as a tool for a forward-looking planning of water resources against the background of Global Change.

Figure 1 schematically shows the «package natural environment» in the Danubia modelling framework considering the hydrological and glaciological processes within the hydrological cycle as they interact with the atmos-

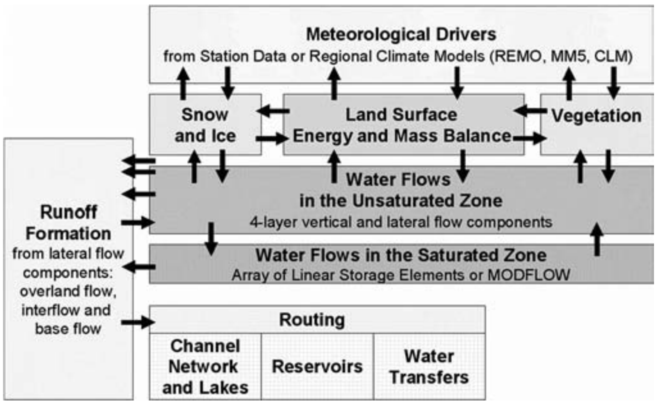


FIG. 1 - Basic structure of the network for natural environment modelling within the Glowa-Danube system (Mauser & Bach, 2009).

phere. It is based on the hydrological Promet model (Processes of Radiation, Mass and Energy Transfer; Mauser & Bach, 2009) which calculates energy and mass fluxes at the surface of small to very large and complex basins in a grid-based, distributed manner. The grid element, also called Process Pixel or Proxel, is generally 1x1 km^2 in size, and the time step of calculations is one hour. For each grid element the accumulation and ablation of the snowpack and the development of the possible glacier surface is calculated using the specific model components Snow and Surges (Subscale Regional Glacier Extension Simulator, for details of the algorithms see Weber, 2010). The glacier model calculates both the surface mass changes and the evolution of glacier geometry over long periods. The model results were validated exemplarily over more than 30 years in the Upper Danube area (Marowsky, 2010) and in Tibet (Prasch, 2010). Specific mass change and area loss is reproduced within an error band of less than 10% of observed differences. As the grid length (spatial resolution) given by the modelling framework is too coarse for the treatment of hydrological processes in strong relief, it was necessary to parameterize the detailed terrain information on each grid element by a subscale area-elevation distribution. On these partial areas the glacier mass balance as well as the contributions from snow-, icemelt and rain runoff are calculated and aggregated on the proxel scale. This event runoff then is routed through a soil hydraulic model and then passed on to a complex runoff model treating the routing and channel flow processes, allowing the calculation of aggregated runoff from almost any tributary basin. All important natural and man-made storage elements in the ground and along the basin network are considered in the calculations. The minimal size of subbasins where runoff can be calculated is given by the prescribed element size and modelling concept, and is in the order of 100 km^2.

The model requires as input a representative set of meteorological variables (precipitation, air temperature, humidity, the components of the radiation budget, horizontal wind, air pressure) for each proxel at a temporal resolution of one hour. This set can be derived from measured values at the stations of the local climatological network, or can be generated from direct results of regional climate models (CLM: Climate Local Model, German Climate Centre, spatial resolution Res. 45 km, time step TS 3 h; Remo: Regional Model MPI Hamburg, Res. > 10 km, TS 1 h; MM5: Mesoscale Model 5, MIM Res. 45 km, TS 1 h).

The linking of the climate model scale with the fine grid scale of Danubia is done with the Scalmet interface (Marke, 2008), which employs statistical-empirical scaling functions. As another alternative, a stochastic weather generator was developed by Mauser & *alii* (2007), which recombines randomly historic climatological datasets for an extensive ensemble of new, synthetic time series, which conserve the physical relations between the meteorological variables (Strasser, 2008). It is based on the statistical analysis of multi-year time series of temperature and precipitation of a network of meteorological stations. Weekly means (temperature), sums (precipitation) and their covariances form the necessary input for a random generation for an arbitrary number of mean temperature and precipitation series, which are equivalent to the historical record. By imposing a trend on temperature and rainfall possible scenarios of regional climate change can be produced on the basis of today's meteorological network. To convert the stochastic trend values of weekly temperature and precipitation into a set of meteorological drivers for the impact models the historical data from the station network is searched for the most similar week in terms of average temperature and precipitation using the Mahalanobis distance as criterion. The measured meteorological data of the selected week from the complete network is inserted into the new artificial data series of the future climate scenario. By using different initial values (seed) for the random number generator a large number of artificial data series, which are statistically equivalent realisation of the transition from the present to a future climate, can be created. By analysing different sources of knowledge on the expected regional climate change (climate models, extrapolations, historical analyses, etc.) a funnel-shaped range is created, which spans a range of uncertainty on future climate projections (fig. 2). Based on the selected climate trend, statistically equivalent variants can be created. The variants differ in the characteristics of the transition, for instance, a larger portion of the temperature change tends to be concentrated in the first part of the modelled decade, or vice versa, in the latter part. Variants with specific properties can be selected from a large number of variants produced from a large number of runs. Each selected variant has a known probability of occurrence. Selection criteria can be prolonged dry periods or a series of particularly warm Winters or hot Summers. Furthermore, a random combination of two variables such as temperature and precipitation may lead to secondary effects in the model results, for instance to a sequence of snow-scarce Winters. In the Glowa-Danube project a total of four sets of trends (IPCC, Remo, MM5 and extrapolation) each with 4 characteristic variants (baseline, 5 consecutive dry years,

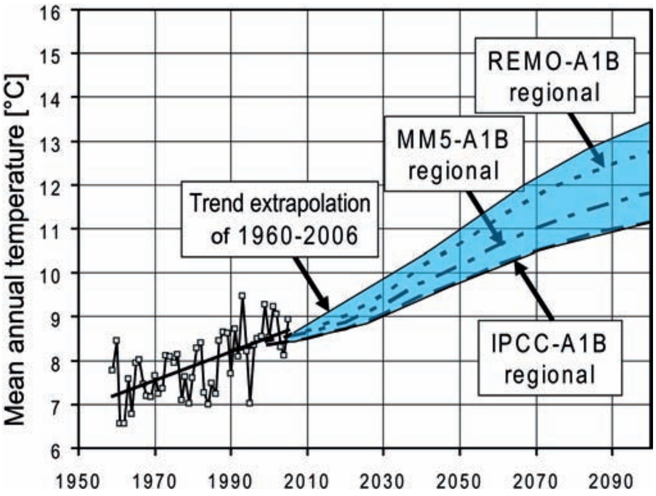


FIG. 2 - Band width of the investigated Glowa-Danube regional climate trends, which are all based on the assumption of the IPCC A1B emission scenario. The modelling results presented in this paper are calculated using the REMO regional baseline option.

5 consecutive hot Summers and 5 consecutive warm Winters) were investigated. The modelling results presented in this paper are calculated using the variant Remo regional baseline.

The hydrological component of Danubia, therefore, allows the calculation of discharge in the river network of large basins with special consideration of the typical high mountain processes and dependencies. The locally produced icemelt at the surface of glaciers, the snow and liquid fractions of precipitation, as well as the amount of snowmelt can be determined quantitatively. It would be desirable to have the option of tracing each water molecule along the river network, with the aim of finding the source region and the composition of runoff. This is the only way that one could accurately determine the origin of the water found in the river. This is not yet possible even with Danubia, as runoff generation is extremely complex. The physically-based approach of the model, however, allows the suppression of selected processes such as icemelt for example, and the resulting changes in runoff can be attributed to the suppressed process, in this case glaciermelt. Compared with the amount of precipitation over the whole basin, the amount of glaciermelt is relatively small and locally confined, and is delivered directly into the river channel system, and as a result, soil water storage and evaporation remain practically unaffected when suppressing glaciermelt in the model runs.

On the other hand, the influence of snow storage on the runoff processes is considerably more complex. As mentioned above, snowmelt is effective over the total snow-covered part of the basin, similar to rain, and the amount is large especially during the snowmelt season in Spring. If the formation of snow storage and melt is suppressed in the model, soil water storage is strongly reduced and evaporation over large areas is altered due to this condition. As a result, the total amounts of runoff with and without snow cover formation are not identical. One can conduct a model run without snow cover by setting the transition air temperature from snowfall to rainfall at absolute zero degrees (0 K), and consequently, precipitation falls always and everywhere as rain. The yearly mean runoff calculated as the integral over the hydrograph without snow cover is slightly lower (< 10%) than the reference run with snow cover due to differing evaporation losses and trends in storage amounts. The differences between the model runs can be calculated over longer balancing periods, but not over several weeks or days. As a result, the integral of the differences of the model runs with and without snow should not be interpreted as a quantitative measure, but only as a qualitative indication of the seasonal contribution of snowmelt water to runoff. With respect to total yearly runoff (without icemelt) the difference can be interpreted as the relative annual contribution of snowmelt. An illustration of this methodology is given in fig. 6.

CHARACTERISTICS OF THE UPPER DANUBE BASIN

The research area of the Glowa-Danube project is the watershed of the Upper Danube situated in Central Europe (fig. 3). Its area of 76,653 km^2 is defined by the gauge Passau/ Achleiten and there more than 10 million inhabitants live. A fraction of 28% of this area (22,000 km^2) lies within the Alps reaching a maximum elevation of 4052 m at Piz Bernina. The elevation belt between 1000 m and 2000 m a.s.l. covers an area of 11,000 km^2, further 5,900 km^2 lie between 2000 and 3000 m a.s.l., and only 300 km^2 (0.38%) exceed the elevation of 3000 m. This uppermost part is mostly glacierized.

These conditions lead to a remarkably broad range of influencing factors on water resources. The Upper Danube is characterised by a complex and intensive use of the water resources for hydropower, farming and tourism.

Precipitation is highly variable throughout the basin, with low values of about 600 mm/y in the lowlands of the northern part, and over 1600 mm/y in the mountains of the alpine fringe towards the south. The inner-alpine valleys have low values similar to the lowlands outside the Alps (fig. 4).

Analysing the glacier inventories of Austria, Switzerland and Bavaria, a total of 556 individual glaciers were found in the basin in the year 2000, covering 358 km^2 corresponding to 0.5% of the basin area. To determine the ice volume ice depth measurements were used, which are available for about 10% of the glaciers. In all other cases it had to be estimated from volume-area-scaling relationships and similarity principles (Weber & *alii*, 2008). The spatial distribution of ice storage is shown in fig. 5, and its total volume is estimated at 16.4 km^2. If distributed over the entire basin, this ice storage corresponds to a potential runoff increase of 213 mm only (see also fig. 8).

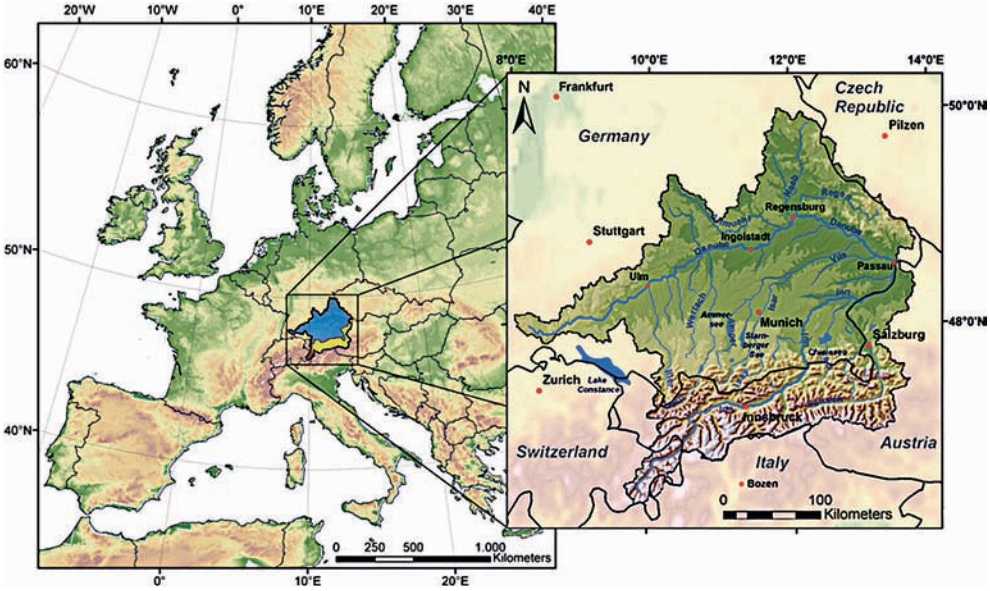


FIG. 3 - Location of the Upper Danube river basin. Basin area is 76 653 km^2 (gauge Passau/Achleiten), elevation ranges from 288 m (Achleiten) to 4052 m (Piz Bernina).

RESULTS 1: RUNOFF CONDITIONS DURING THE OBSERVATION PERIOD 1991-2000

With the aid of the above-mentioned dynamic snow and glacier model the amounts of snow- and icemelt as well as rain could be calculated at any position within the river network under current and future climatic conditions. Fig. 6 gives the seasonal distribution of these runoff components for the gauging station Passau/Achleiten for the decade 1991 to 2000, where 2% of annual runoff stems from icemelt, 22% from snowmelt, and 76% from rain as shown in the inserted circular diagram. By excluding glaciermelt in the runoff calculation the reduction of runoff can be directly attributed to the portion which stems from icemelt. This portion is large in the head watersheds, but gradually becomes smaller downstream as can be seen in fig. 7. When following the Oetztaler Ache tributary of the Inn River from Vent to Huben for example, the relative annual contribution of icemelt is reduced from 35 to 25%, takes on a value of 8% in Innsbruck, is reduced to 6% at Oberaudorf where the Inn leaves the Alps, and finally is down to 2% in Passau/Achleiten after the confluence of Inn and Danube.

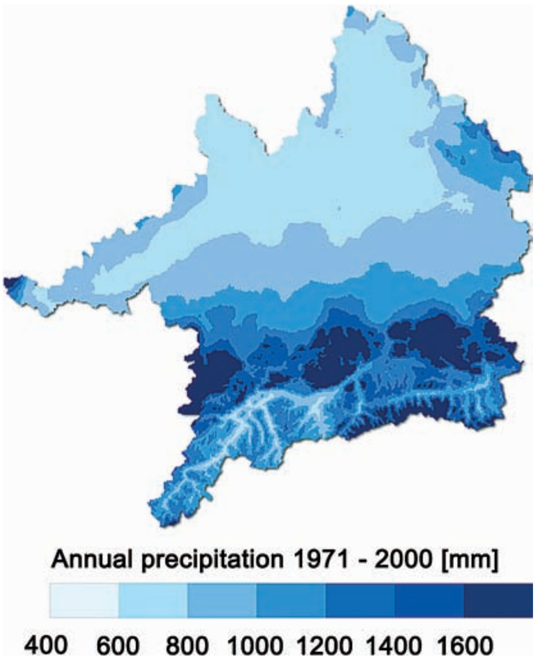


FIG. 4 - Distribution of annual precipitation in the Upper Danube river basin 1971-2000, calculated from data of the meteorological stations network according the procedures described by Mauser & Bach (2009).

Apart from showing the relative portions of runoff at given gauging locations, fig. 7 also gives the amount of snowmelt relative to total runoff of the contributing basin above each point (proxel) of the river network. In the lowland basins this relative amount is always below 20% (orange and red). In the alpine region, the relative importance of the snow cover in the formation of runoff is very much higher, the highest contribution being observed in the valleys of the northern alpine rim, indicated by the blue colouring of the river network (above 50%). In the glacierized head watersheds, the importance of snowmelt is in competition with glacier icemelt, and as a result the relative importance of snowmelt is lower as compared to glacier-free basins. The overall high amount of snowmelt in the alpine region is exported to the lowland through the rivers with source regions in the mountains, such as the Isar or the Lech with more than 30% snowmelt indicated in yellow, which is considerably higher than the neighbouring basins not connected to the Alps. Similarly, the rivers originating in the high elevations of the Bavarian Forest region have a higher proportion of snowmelt.

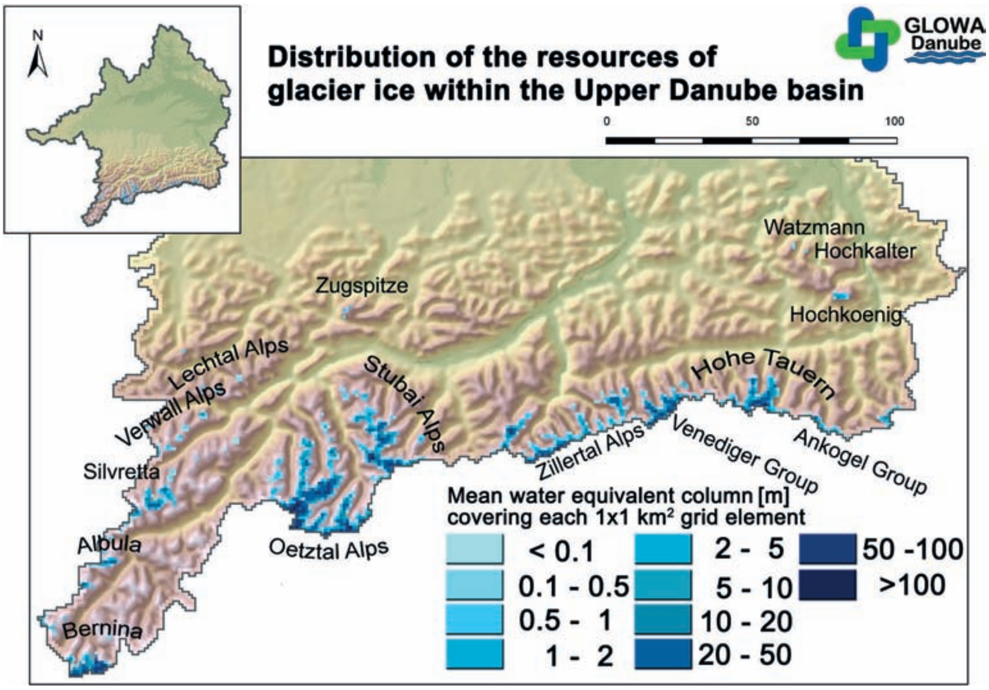


FIG. 5 - Glacier ice storage in the Upper Danube river basin as mean water column [m] over each 1x1 km^2 proxel.

Another important indicator of the hydrological productivity of a basin is its annual specific runoff**.** In fig. 7 these values are given in the overall size (area) of the circular diagrams for selected gauging stations. Generally speaking, the inner-alpine basins have high specific runoff values of up to 1500 mm per year and a relative contribution of snowmelt of over 40% at some locations, while similar-sized lowland basins yield only 300 to 600 mm per year with a portion of snowmelt of about 15%. The river segments with source regions in the Alps export the high discharge values in the direction of the lower Danube, as is especially obvious for the Isar River flowing through Munich. Here, the mean specific runoff is about 1000 mm with a relative portion of snowmelt of 33%, a runoff value which is even above the local precipitation amount. In comparison, for the Amper River at Inkofen with a similar basin area but without alpine source region, the mean specific runoff is only about 600 mm per year with a snowmelt portion of 15%. The «distance» or «long-range» effect of rivers with alpine source regions diminishes further downstream, as the snowmelt waters are «diluted» by the rainwater of the lowland tributaries, but nevertheless, the specific runoff values and the snowmelt portions are visibly higher just above the junction with the lowland rivers. When looking at the Danube at Passau/Achleiten it is obvious that due to the high specific runoff and snowmelt amounts in the Inn draining, to a large extent, the alpine part of the Danube basin, the overall water yield of the Danube River is enhanced by the alpine contribution.

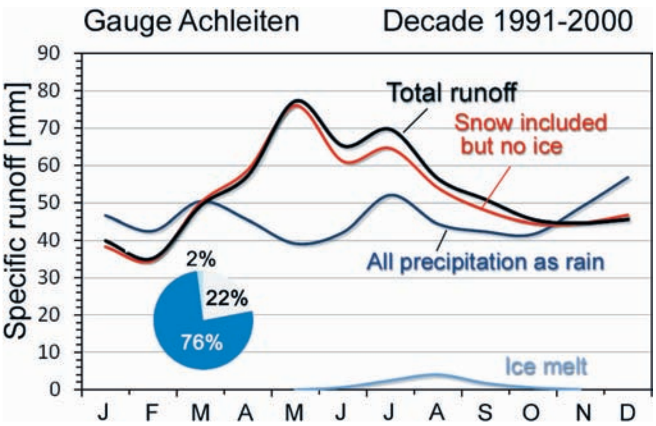
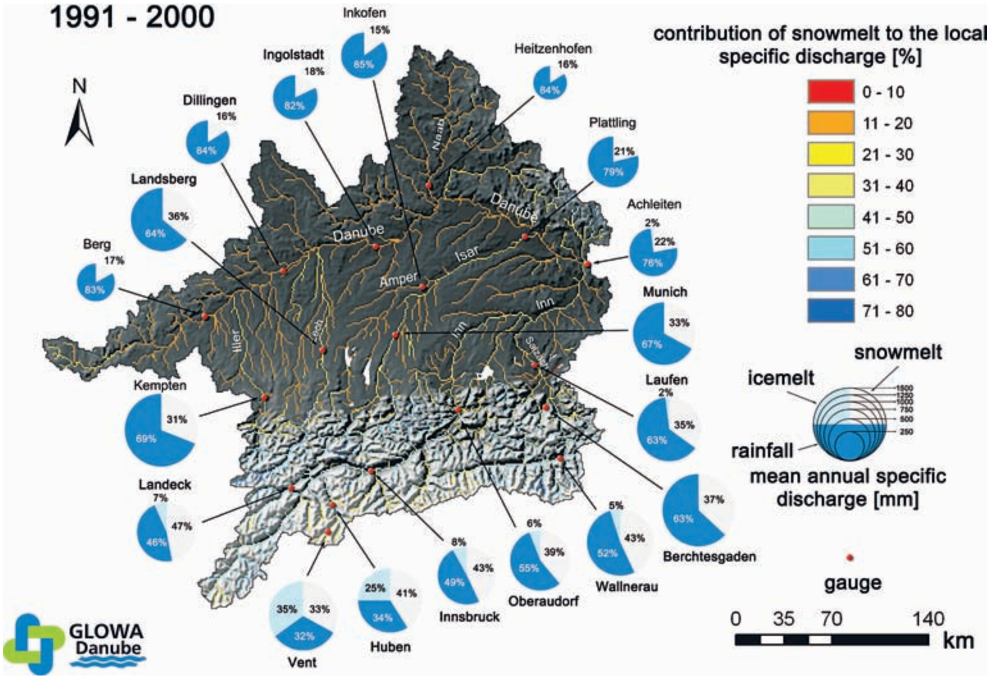


FIG. 6 - Seasonal distribution of runoff of the Upper Danube at Passau/Achleiten. From total runoff the icemelt segment is subtracted in a first step (snow included but no ice), and in a second step the formation of snow is suppressed (all precipitation as rain). In this way, the relative amount of rain, snow and icemelt in the formation of annual runoff can be given in the form of a circular diagram.

RESULTS 2: FUTURE RUNOFF CONDITIONS UNDER THE ASSUMPTION OF CLIMATE WARMING

How will the relative importance of rain, snow- and icemelt change under the assumption of a continued climate warming? Of course the changes will depend to a large extent on the development of the climate parameters in the selected climate scenario. Glowa-Danube provides a bundle of alternative scenario datasets (Kuhn & *alii*, 2009). Here, the results are presented using simulations driven by the Remo regional-baseline scenario, which is rather moderate in comparison to other scenarios, and the extrapolation of the 1960 to 2006 trend investigated in the Glowa-Danube project (see fig. 2).

FIG. 7 - Upper Danube basin showing the contribution of snowmelt to runoff at each location along the river network, and mean annual specific runoff at selected gauging stations together with the relative contribution of rainfall, snowmelt and icemelt for the period 1991-2000.



The related meteorological input data are provided by the climate data generator (for details see Mauser, 2009a) as mentioned above. The recombined data series shows a prescribed trend in mean temperature of +5.2K within the period from 1990 to 2100, according to the regional results of the Remo climate model (Mauser & *alii*, 2009). Within the same period, the winter precipitation sum increases by 7%, in contrast, summer precipitation decreases by 34%. The term «baseline» refers to the selection of a medial transition of the change in temperature. Hence this scenario is basically characterized by dry summer periods in the future.

The first decade (2011-2020, see fig. 9a) results in a sequence of snow-scarce Winters, and as a consequence, the poorly developed snow cover melts out rapidly, giving rise to very high icemelt from the snow-free parts of the glaciers despite air temperatures that are only moderately higher than today (see Rofenache/Vent: specific runoff 1850 mm, 51% of which is icemelt, fig. 9c). In this decade total ice storage in the Inn basin is reduced by 2/3 of the current value of about 210 mm water column as a mean over the total Upper Danube basin, almost independent of the chosen scenario (fig. 8). In the future, winter precipitation is expected to increase, and as a result snow storage may increase at higher elevations during the decade 2021 to 2030 despite of rising air temperature. However, in the long run and seen over the whole Upper Danube basin, the volume of snow storage will diminish, and the runoff portion of snowmelt will fall below 10% in the lowland basins. But also within the Alps there will be drastic changes: in the head watersheds icemelt will be greatly diminished due to the strong reduction in glacierized area, and as a result, snowmelt and rain will temporarily gain in importance, but they cannot compensate the loss of icemelt. As a whole, specific runoff will decline, and the portion of runoff from rain will increase at the cost of snowmelt, i.e., the nival regime will move towards a more pluvial one. The rivers with alpine source regions will continue to export excess water to the lowlands in the decade 2031 to 2040; beyond this time, however, the general decline in anticipated precipitation will reduce specific runoff also in basins with an alpine connection.

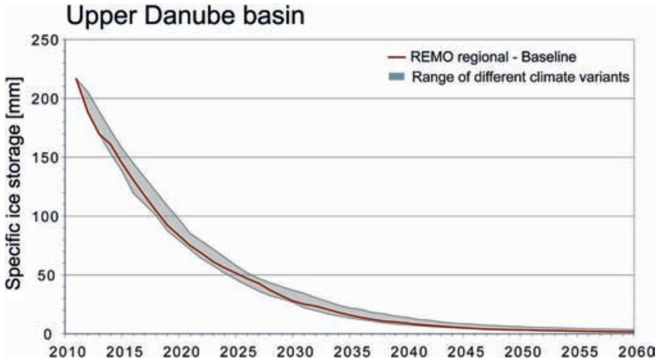


FIG. 8 - Modelled reduction in ice storage as a result of the presented scenario Remo regional baseline (line). The range of all investigated scenario variants is shown in grey colour.

In the last investigated decade 2051-2060 the changes in runoff production are drastic both in and outside of the Alps in comparison with the current situation. During dry spells in Summer the former glacial streams will dry up almost completely, and the snowmelt portion of runoff in the alpine areas will be as low as in the current lower

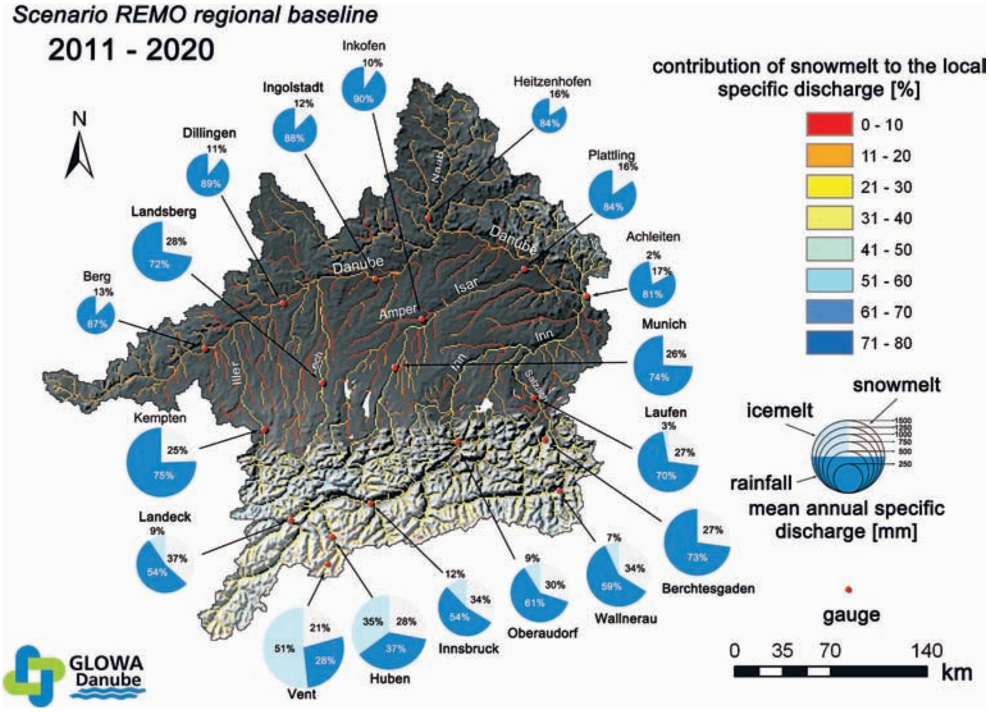


FIG. 9a - Contribution of snowmelt along the river network of the Upper Danube River, and the relative contribution of rain, snow-and ice-melt at selected gauging stations based on the Remo regional baseline scenario 2011-2020.

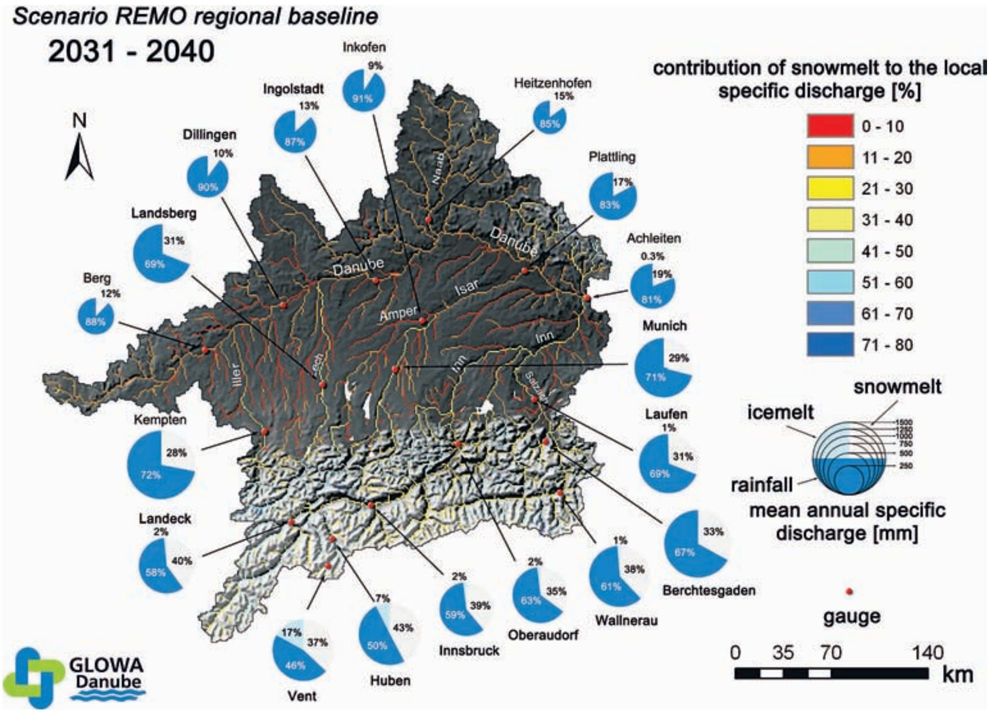


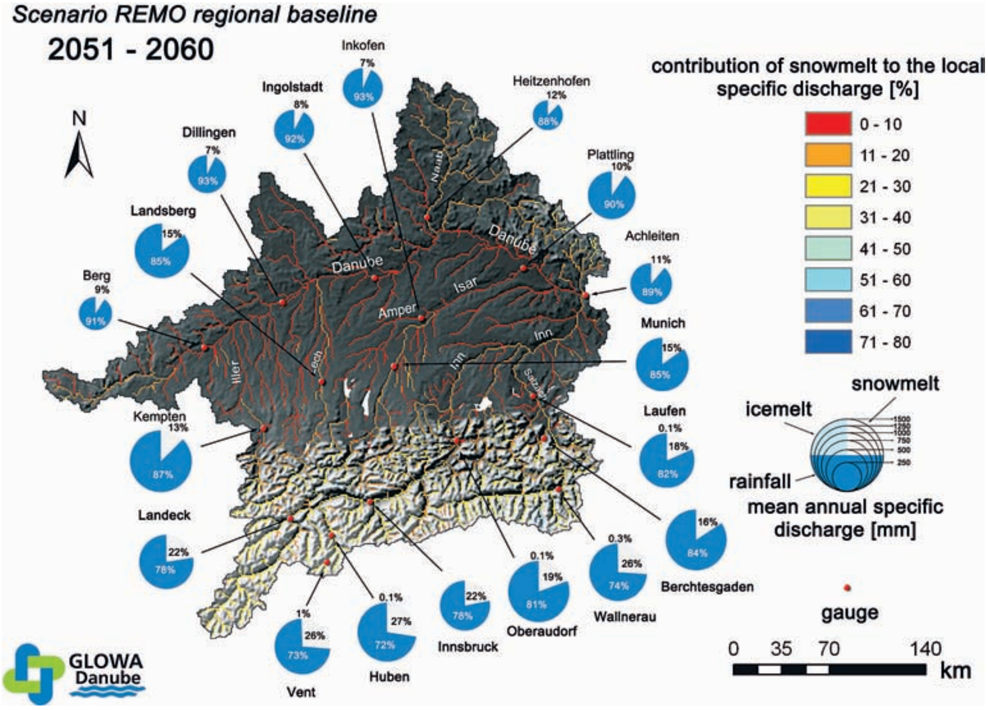
FIG. 9b - Contribution of snowmelt along the river network of the Upper Danube River, and the relative contribution of rain, snow-and icemelt at selected gauging stations based on the Remo regional baseline scenario 2031-2040.

alpine regions outside the alpine arc. The runoff regime is a pluvial one in almost the entire Upper Danube basin, which means that runoff is almost exclusively controlled by rainfall. With a further reduction in precipitation amounts in Summer the specific runoff will diminish in the whole Danube basin, and the function of the Alps as «water towers» will be reduced.

CONCLUSIONS

The function of the Alps as the «water towers» of Europe is the result of enhanced precipitation amounts falling in the mountainous regions and the formation of a massive snowpack, the melting of which maintains high runoff values up to early Summer. While the relative por-

FIG. 9c - Contribution of snowmelt along the river network of the Upper Danube River, and the relative contribution of rain, snow and icemelt at selected gauging stations based on the Remo regional baseline scenario 2051-2060.



tion of glacier icemelt is up to one third in the head watersheds today, its portion downstream diminishes rapidly, with only 2% of annual runoff being of glacial origin at Passau/Achleiten during the observation period 1991 to 2000. Under the assumption of a further (moderate) global warming and reduced precipitation in the summer months, the role of the Alps in exporting excess water will be reduced drastically in about 50 years**,** mainly due to the fact that snow storage will be much lower and evaporation will be greater (Hank, 2009). The loss of glaciers will result in a substantial reduction of runoff in the head watersheds during Summer, but will not have a marked effect outside the alpine arc.

REFERENCES

HANK T. (2009) - *Entwicklung der Verdunstung heterogener Landoberflächen unter Szenarienbedingungen*. Kapitel 3.1.6, Glowa-Danube-Projekt, LMU München (Hrsg.), Global Change Atlas. Einzugsgebiet Obere Donau, München.

HUSS M., FARINOTTI D., BAUDER A. & FUNK M. (2008) - *Modelling runoff from highly glacierized alpine drainage basins in a changing climate*. Hydrological Processes, 10. 1002/hyp.7055, 22 (19), 3888-3902.

KOBOLTSCHNIG G.R., SCHÖNER W., ZAPPA M. KROISLEITNER C. & HOLZMANN H. (2008) - *Runoff modelling of the glacierized alpine Upper Salzach basin (Austria), Muliti-critera result validation*. Hydrological Processes, 22, 3950-3964.

KUHN M., ABERMANN J., OLEFS M., FISCHER A. & LAMBRECHT A. (2009) - *Gletscher im Klimawandel: Aktuelle Monitoringprogramme und Forschungen zur Auswirkung auf den Gebietsabfluss im Ötztal*. Mitteilungsblatt des Hydrographischen Dienstes in Österreich, 86, 31-47.

KUHN S., ERNST A. & MAUSER W. (2009) - *Glowa-Danube Szenarien.* Kapitel S1, Glowa-Danube-Projekt, LMU München (Hrsg.), Global Change Atlas. Einzugsgebiet Obere Donau*,* München.

MAROWSKY K. (2010) - *Die Validierung des Gletschermodells Surges am Beispiel von Vernagtferner sowie Nördlichem und Südlichem Schneeferner*. Unpublished diploma thesis, Kath. Univ. Eichstätt-Ingolstadt, 147 pp. - http://www.glaziologie.de/download/DAMarowsky2010.pdf

MAUSER W. (2009a) - *Der statistische Klimaantriebsgenerator.* Kapitel S3, Glowa-Danube-Projekt, LMU München (Hrsg.), Global Change Atlas. Einzugsgebiet Obere Donau*,* München.

MAUSER W. (2009b) - *Die Glowa-Danube Klimavarianten aus dem statistischen Klimagenerator.* Kapitel S4*,* Glowa-Danube-Projekt, LMU München (Hrsg.), Global Change Atlas. Einzugsgebiet Obere Donau, München.

MAUSER W. & LUDWIG R. (2002) - *Glowa-Danube - A research concept to develop integrative global changes of the water cycle*. In: Beniston M. (Ed.): «Climatic Change: Implications for the Hydrological Cycle and for Water Management». Advances in Global Change Research, 10, Kluwer Academic Publishers, Dordrecht and Boston, 171-188.

MAUSER W. & BACH H. (2009) - *Promet - Large scale distributed hydrological modelling to study the impact of climate change on the water flows of mountain watersheds*. Journal of Hydrology, 376, 362-377.

MAUSER W., PRASCH M. & STRASSER U. (2007) - *Physically based Modelling of Climate Change Impact on Snow Cover Dynamics in Alpine Regions using a Stochastic Weather Generator*. In: Oxley L. & Kulasiri D. (Eds) - «Modsim 2007», International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2007, 2138-2145.

MAUSER W., MARKE T. & REITER A. (2009) - *Die Glowa-Danube Klimatrends.* Kapitel *S2,* Glowa-Danube-Projekt, LMU München (Hrsg.), Global Change Atlas. Einzugsgebiet Obere Donau*,* München.

Prasch M. (2010) - *Distributed Process Oriented Modelling of the Future Inpact of Glacier Melt Water on Runoff in the Lhasa River Basin in Tibet*. PhD-thesis, Faculty of Geosciences, University of Munich (LMU), 226 pp.

Strasser U. (2008) - *Modelling of the mountain snow cover in the Berchtesgaden National Park*. Forschungsbericht, 55, Nationalparkverwaltung Berchtesgaden, 104 pp.

Weber M. (2010) - *Das Gletschermodell Surges. Documentation of the glacier model SURGES, internal report in German*. Commission for Glaciology, Bavarian Academy of Sciences, 71 pp. www.Glaziologie.de/Download/Surges2010.pdf

Weber M., Prasch M., Kuhn M., Lambrecht A. & Hagg W. (2008) - *Eisreserve-Teilprojekt Glaziologie.* Kapitel 1.8, Glowa-Danube-Projekt, LMU München (Hrsg.), Global Change Atlas. Einzugsgebiet Obere Donau, München.

Weber M., Braun L., Mauser W. & Prasch M. (2009) - *Die Bedeutung der Gletscherschmelze für den Abfluss der Donau gegenwärtig und in der Zukunft*. Mitteilungsblatt des hydrographischen Dienstes in Österreich, 86, S. 1-29.

Wehren B., Weingartner R., Schädler B. & Viviroli D. (2010) - *General Characteristics of Alpine Waters.* In: U. Bundi (Ed.), «Alpine Waters», Hdb Env Chem (2010) 6, 17-58, DOI 10.1007/978-3-540-88275-6-2, Springer-Verlag Berlin Heidelberg 2010.

More detailed information

http://www.glowa-danube.de/atlas/atlas.php

http://www.glaziologie.de/forsch.html

(Ms. received 30 August 2010; accepted 30 November 2010)