

The Alps under climate change: implications for water management in Europe

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ABSTRACT

The Alps function as a water tower for four of the major European river basins. However, a climate change-induced shift in mountain hydrological regimes and the future predicted disappearance of Alpine glaciers at the end of this century will have consequences for water management in both the Alps and the water-dependent lowlands. In this paper the importance of mountain water in the European lowlands and the impact of climate change on the water sector in both the mountains and lowlands are shown. Different demand stakeholders of the Alpine water sector will be affected. Dependent on the particular region in the Alps, problems will be less or more severe but generally adaptation can be achieved by means of the right investments and policies. However, major impacts on the water sector in the lowlands of the Danube, Rhine, Rhone and Po river basins are foreseen. Integrated water management at basin level is required to cope with these challenges.

Key words | Alps, glacier, mountain water, snowpack, water resources management

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INTRODUCTION

Mountains are a water reservoir for many regions of the world (Viviroli *et al.* 2003, 2007, 2011; Viviroli & Weingartner 2004; Weingartner *et al.* 2007; de Jong *et al.* 2009). Numerous river basins rely strongly on their mountainous parts for water because of the effect of rain accumulation at high altitudes, specific hydrogeology and the storage of water in the form of snow and ice. The latter is true for regions with substantial seasonal snowpacks (Barnett *et al.* 2005) and glaciers (Kaser *et al.* 2010).

Climate change will affect mountain hydrology significantly, with important consequences for water availability in both upstream and downstream parts of river basins. Mountainous areas are particularly vulnerable to temperature and precipitation changes (Beniston 2003). In the European Alps, the 20th-century warming has been roughly three times the global average (Jungo & Beniston 2001). Mountains are also early indicators of climate change. Many climatologists believe that the changes occurring in mountain ecosystems provide an early glimpse

of what may come to pass in lowland environments. Changes in glacier length and volume are widely recognised as the most reliable and most easily observed terrestrial indicators of climate change (Paul *et al.* 2007). Alpine glaciers lost 35% of their total area from 1850 until the 1970s, and almost 50% by 2000 (Zemp *et al.* 2006). Total glacier volume around 1850 is estimated at some 200 km³, in 1970 at 130 km³ and it is now close to one-third of the 1850 value (Haeberli & Beniston 1998; Zemp *et al.* 2006). If current trends continue, by the end of this century these glaciers will have vanished entirely.

This review gives a general overview on the following topics: (1) Alpine hydrology and the importance of mountain water for the lowlands of the Rhine, Danube, Rhone and Po river basins; (2) why and how these hydrological regimes will shift in future due to climate change; (3) how the latter will affect water management in the Alps; and (4) how water management in the lowlands is affected.

ALPINE HYDROLOGY AND ITS IMPORTANCE FOR THE EUROPEAN LOWLANDS

The Alps feed four of Europe's largest river basins: the Danube, Rhine, Rhone and Po (Table 1). Their cumulative area accounts for about 11% of the total European continent. However, their lowlands are characterised by high population densities and industrialisation, comprising large parts of the economically most important regions in Europe.

In *Viviroli et al. (2007)* the Alps are defined as a mountain type with medium or high contributing potential to the wet lowland of the four assessed river basins. With a mean annual contribution of 26% of the total discharge, the mountain region of the Danube system (10% of total area) supplies 2.6 times more water than might be expected on the basis of surface area alone (*Weingartner et al. 2007*). Similarly, the Alpine part of the Rhine basin (15%) contributes 34% of total discharge, resulting in a disproportional influence of 2.3. The mean annual contribution of the Alps in the Rhone and Po basins (where the areal proportion of the Alps is 23 and 35%, respectively) accounts for 41 and 53%, respectively, implying a disproportional influence of 1.8 and 1.5. The importance of mountain water differs depending on the season. Whereas the Alpine part of the Rhine contributes less than 30% of total discharge during the winter months, this value increases to more than 60% during the summer months of June to September (Figure 1). Similarly the contribution of the Alpine River Inn (3.2% of total area) to the total discharge in the Danube basin accounts for a minimum of 6.6% during the winter months and a maximum of 18.5% in August.

Altitude is certainly the most distinguishing and fundamental characteristic of mountain climates, because atmospheric density, pressure and temperature decrease with height in the troposphere (*Beniston 2006*). Typical for

mountains are rapid and systematic changes in climatic parameters, in particular temperature and precipitation, over very short distances. In the Alps, temperature decreases and precipitation increases (orographically enhanced precipitation) with altitude (*Sevruk 1997*). Accordingly evapotranspiration decreases with altitude and both snow cover duration and volume – also dependent on exposure – increase with altitude (*Slatyer et al. 1984; Vanham et al. 2008*). For Austria, for example, *Schöner & Mohnl (2003)* found an average of approximately 10 days lengthening in snow cover duration for each 100 m increase in elevation. Characteristics of the hydrological balance components are thus very different in mountainous catchments compared with lowland catchments. For the period 1931–1960, average annual hydrological water balance components showed significant differences in magnitude between the Alps and the rest of Europe (*Baumgartner et al. 1983*): in the Alps the annual precipitation of 1,460 mm resulted in an evapotranspiration of 480 mm and a runoff of 980 mm, whereas for the rest of Europe the annual precipitation of 780 mm resulted in an evapotranspiration of 510 mm and a runoff of 270 mm. The latter shows the importance of Alpine water for European lowlands.

The comparison of the mean monthly hydrological water balance components between a glacierised high mountain, a non-glacierised middle mountain and a lowland catchment within the Danube river basin shows why the importance of mountain water differs according to the season (Figure 2). As there is more precipitation and less evapotranspiration, the mountainous catchments are characterised by higher discharge values (1,173 mm/yr for the Obere Ötztaler Ache and 1,059 mm/yr for the Brixentaler Ache catchments) than the lowland catchment of the Mattig (512 mm/yr). Owing to high proportions of snow and ice melt water, the high mountain catchment has its

Table 1 | General characteristics of the river basins Danube, Rhine, Rhone and Po

River basin	Basin area, km ²	Mountain area (%)	Mean annual contribution Alps to total discharge (%)	Disproportional influence (see text)	Glacier area, km ² (%)	Population, 10 ⁶	Population density (people per km ²)	Number of countries
Danube	794,133	10	26	2.6	617 (0.08)	81.38	103	19
Rhine	190,713	15	34	2.3	459 (0.24)	59.07	310	9
Rhone	97,702	23	41	1.8	1,162 (1.19)	10.12	104	2
Po	73,297	35	53	1.5	818 (1.12)	16.55	226	3

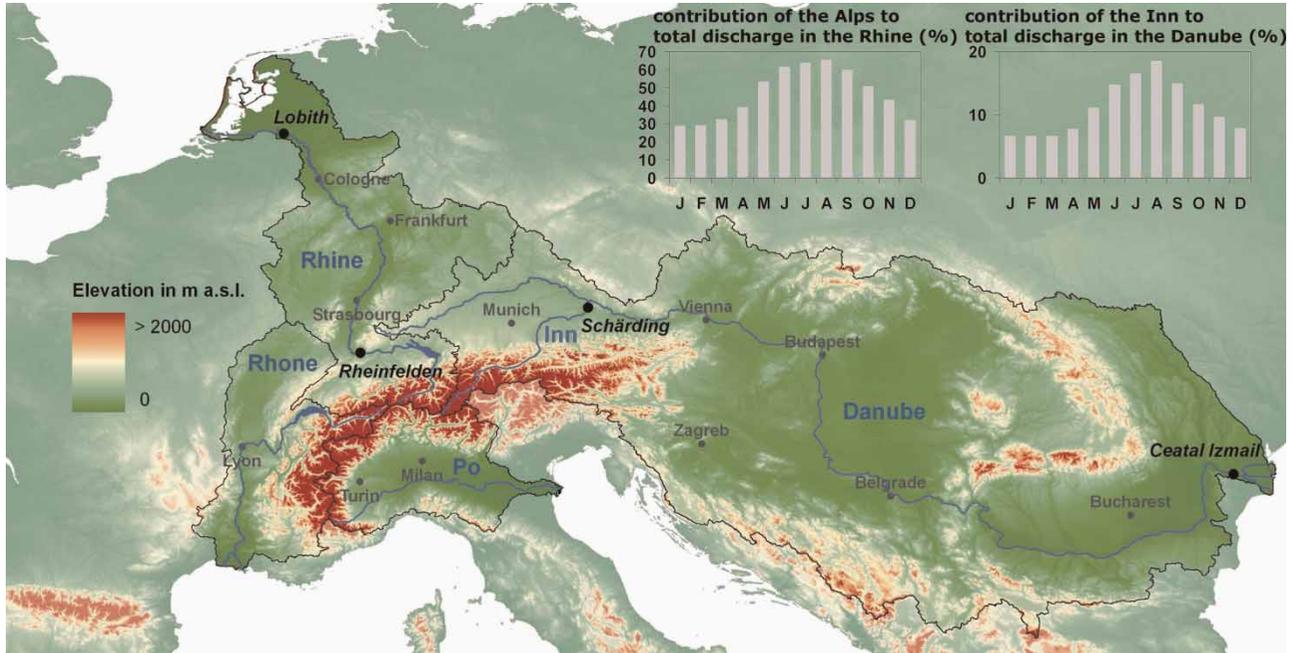


Figure 1 | Mean monthly contribution of Alpine water to total flow in the Rhine and Danube catchments, for the climate reference period 1961–1990. The proportion of mountain water for the Rhine basin is defined as the discharge measured at the Rheinfelden gauge relative to the discharge measured at the Lobith gauge. The importance of mountain water for the Danube basin is shown by the contribution of the Alpine Inn subcatchment by means of the proportion of the discharge measured at the Schärding gauge relative to the discharge measured at the Ceatal Izmail gauge.

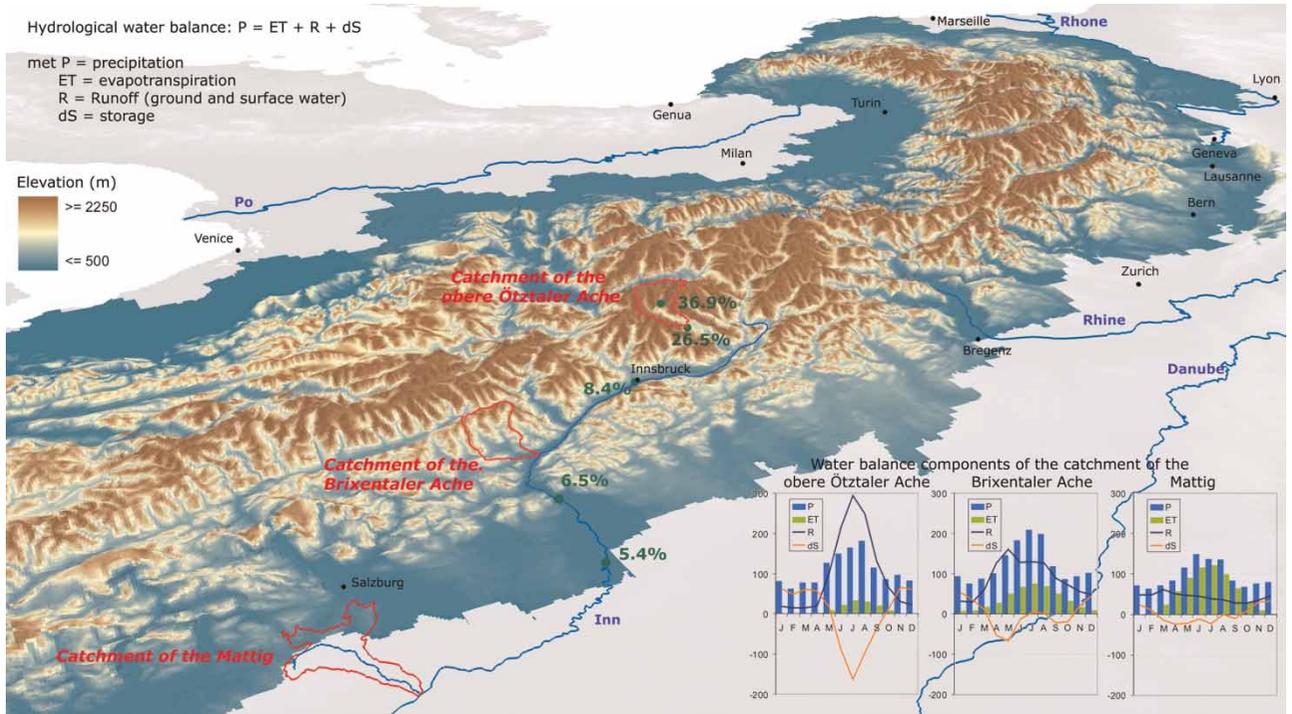


Figure 2 | Mean monthly hydrological water balance components (in mm for the period 1961–1990) of three subcatchments of the Danube basin: (1) the high mountain glacierised catchment of the obere Ötztaler Ache with an average altitude of 2,625 m a.s.l.; (2) the non-glacierised middle mountain catchment of the Brixentaler Ache with an average altitude of 1,326 m a.s.l.; and (3) the lowland catchment of the Mattig with an average altitude of 613 m a.s.l. The green points indicate the proportion of glacial melt water to mean annual total discharge of the Inn and its tributary Ötztaler Ache for the period 1991–2000 (Weber *et al.* 2009, 2010). The full colour version of this figure is available online at <http://www.iwaponline.com/jwc/toc.htm>.

highest discharge values during the summer months, whereas the middle mountain catchment has its biggest snowmelt phase during spring. The lowland catchment is characterised by lower discharge values during summer and autumn, compared with the high and middle mountain catchments. Especially from late spring to autumn, mountain water thus contributes significantly to the total discharge in the Inn river and other tributaries of the Danube as well as the Danube itself. The contribution of snow and glacial melt water diminish with distance, however (Koboltschnig *et al.* 2008; Brown 2010; Kaser *et al.* 2010). The glacial melt contribution to the lowlands of the Danube and Rhine is very low (maximum monthly contribution approximately 1% at the Alpine border of the lowlands) (Kaser *et al.* 2010), but the contribution to the lowlands of the Po and Rhone is more substantial (maximum monthly contribution about 8 and 10%, respectively, at the Alpine border of the lowlands) (Kaser *et al.* 2010).

CLIMATE CHANGE-INDUCED SHIFT IN HYDROLOGICAL REGIMES

The European Alps are by far the best known mountain area of the world in terms of weather and climate and related environmental characteristics (Beniston 2006). They are influenced by a number of different climatological regimes: Mediterranean, continental, Atlantic, Polar and occasionally Saharan (Beniston *et al.* 1997).

The magnitude and intensity at which climate change will alter the climate in Europe is dependent on the scenarios used. There are, however, some consistencies in the projections (Shabalova *et al.* 2003; Giorgi *et al.* 2004; Christensen & Christensen 2007; Hagemann *et al.* 2009; Smiatek *et al.* 2009; Hurkmans *et al.* 2010). The European region undergoes substantial warming in all seasons. Precipitation changes are highly uncertain until 2050, but by the end of the 21st century there will be wetter winters and drier summers. In winter, precipitation increases over most of Europe (except for the southern Mediterranean regions) because of increased storm activity and higher atmospheric water vapour loadings. In summer, a decrease in precipitation is projected over most of western and southern Europe (including the Danube basin; Hagemann *et al.* 2009).

Precipitation changes in the intermediate seasons (spring and autumn) are less pronounced than in winter and summer. Extreme events are more likely to occur.

A robust finding in the literature is that the Alpine snow volume and snow cover duration will decrease considerably in future (Breiling & Charamza 1999; Beniston *et al.* 2003; Jasper *et al.* 2004; Vanham *et al.* 2009a, b). This reduction increases with decreasing altitudes; that is, low mountain ranges are more affected than middle mountain ranges. In Switzerland, for example, a temperature increase of 4 °C (a potential scenario for 2071–2100) with respect to the reference period 1961–1990 would result in the following reductions of snow volume: 90% at an elevation of 1,000 m, 50% at 2,000 m and 35% at 3,000 m (Beniston *et al.* 2003). At very high elevations the projected increased winter precipitation in the Alps could increase the snowpack (Zierl & Bugmann 2005). However, the low-lying regional losses seem to outweigh the possible increases at high elevations (Beniston *et al.* 2003). The major decreases in Alpine snowpack and an overall shorter duration of snow cover – the end of the winter season is more affected than the beginning – result in earlier snowmelt runoff and a shift in the Alpine river regimes. The fraction of the spring and summer runoff are expected to decline. The Alpine mountain range will lose some of its function as seasonal water storage. Snowmelt-derived runoff will arrive increasingly earlier. Numerous studies with these findings have been conducted for the Alps (Etchevers *et al.* 2002; Shabalova *et al.* 2003; Jasper *et al.* 2004; Zierl & Bugmann 2005; Horton *et al.* 2006; Lenderink *et al.* 2007; Bavay *et al.* 2009; Stewart 2009; Vanham *et al.* 2009a, b; Dobler *et al.* 2010; Hurkmans *et al.* 2010; Junghans *et al.* 2011). An analysis of climate change effects on the hydrology of the middle mountain range Kitzbüheler Ache subcatchment in the Danube basin, shows the predicted shift in hydrological regime from snow-rainfall dominated to primarily rainfall dominated (Vanham *et al.* 2009a, b) (Figure 3).

These changes in the Alpine part of the four assessed catchments – a decrease of the contribution of snowmelt to streamflow and a shift of the timing of the snowmelt season to earlier in the year – contribute significantly to streamflow changes of the rivers Danube, Rhine, Rhone and Po in the lowlands. By the end of the century, average streamflow of these rivers is projected to increase in winter and spring

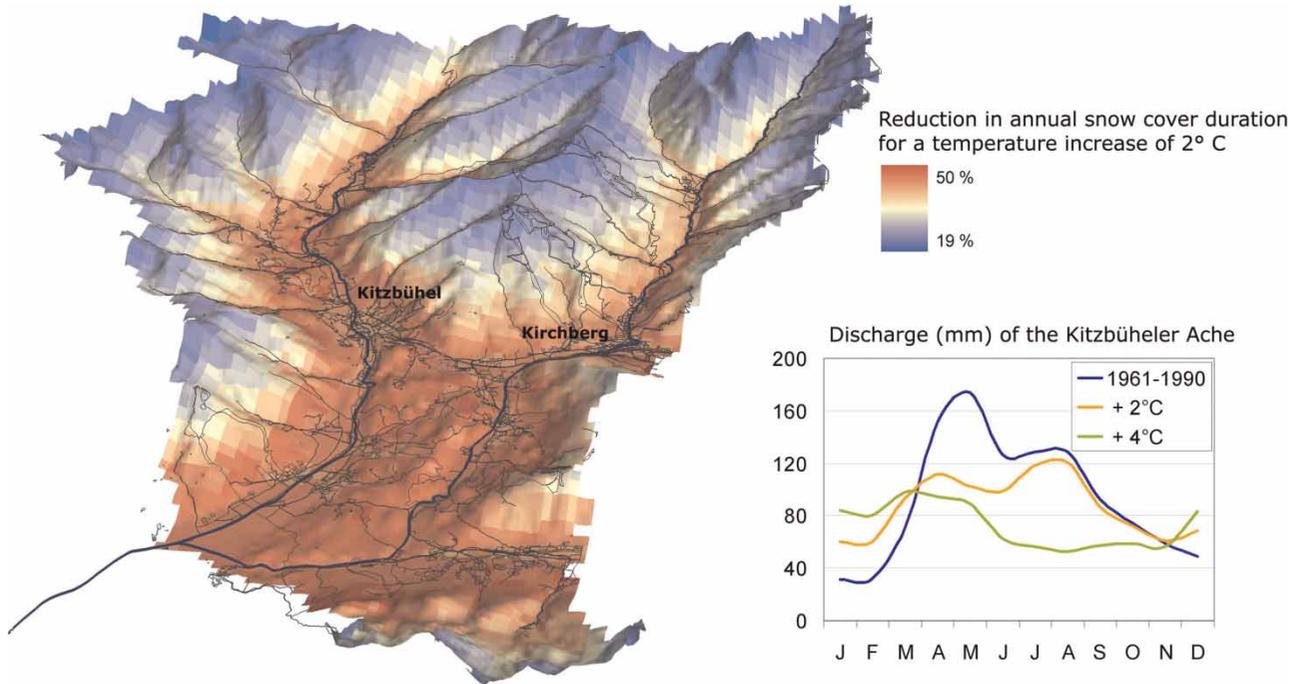


Figure 3 | Reduction in average annual snow cover duration within the Kitzbüheler Ache subcatchment in the Danube basin for a temperature increase of 2 °C with respect to the reference period 1961–1990. Shift in discharge regime projected for a 2 and 4 °C temperature increase (Vanham *et al.* 2009a, b).

because of increased precipitation and snowmelt. Average streamflow is projected to decrease in summer and autumn because of increased evapotranspiration, less snow buffering and decreased precipitation. In addition, considerable increases in the frequency and magnitude of both peak flows and streamflow droughts are projected. An increase of winter flood events is foreseen. These changes are predicted for the Rhine (Shabalova *et al.* 2003; Lenderink *et al.* 2007; Hurkmans *et al.* 2010), the Rhone (Etchevers *et al.* 2002; Boé *et al.* 2009), the Danube (Hagemann *et al.* 2009) and the Po (Coppola *et al.* 2008). For the Rhine, for example, average streamflow at basin outlet is projected to increase by about 30% in winter and spring and to decrease by 30–40% by the end of the 21st century (Shabalova *et al.* 2003; Lenderink *et al.* 2007).

IMPLICATIONS FOR WATER MANAGEMENT IN THE ALPS

In the European Alps, drinking water supply systems are characterised by a local, small-scale infrastructure

(Vanham *et al.* 2011). Water supply is generally organised on a municipal basis. In Austria, for example, a total of 7,600 public water supply companies provide the national population of 8.2 million inhabitants with drinking water (Schoenback *et al.* 2004). Table 2 shows the significant differences amongst selected countries in Europe. Alpine countries such as Austria and Switzerland are characterised by an average low number of people served per undertaking.

Table 2 | Average population served per water supply undertaking in selected European countries; updated information from Schoenback *et al.* (2004)

Country	Number of water supply undertakings	Population, 10 ⁶	Population served per water supply undertaking
Austria	7,900	8.2	1,038
Switzerland	3,000	7.6	2,533
Germany	6,700	82.3	12,284
France	2,350	62.8	26,723
Belgium	72	10.4	144,444
Netherlands	10	16.8	1,680,000
England and Wales	22	51.4	2,336,364

Water supply undertakings in northern European countries with a flat topography such as the Netherlands, Belgium and England, in contrast, generally serve a large number of people. Germany and France present on a national scale a situation between these two extremes. However, on a regional level the small-scale water supply undertakings are concentrated in the mountainous parts of these countries, whereas large undertakings are concentrated in the lowlands. Also typical for Alpine regions, drinking water supply systems are fed by mountain springs and groundwater wells. Surface water is generally not used.

Future regional problems for domestic and municipal water supply security in the Alpine region related to climate change are not foreseen (Vanham *et al.* 2009a). Competition with other stakeholders, however, can become stronger. Longer periods of drought can result in local problems, but with the right investments – the installation of connection pipes between different water supply systems and water-saving practices – these can be solved (Vanham *et al.* 2009a). It has to be stressed that water availability both currently and in future is high, whereas the current and future domestic and municipal water demand is just a small fraction of this availability because of the low population densities. About 13.2 million people reside within the total Alpine area (Alpine Convention 2009), representing a population density of 69 people per km². Even at times of peak demands during the main tourist season – when the populations of certain municipalities increase explosively in size – the demand is just a small fraction of regional availability.

Both the industrial and agricultural water sectors will be affected by the future change in water availability. Industrial water demands are, however, not high in the Alps as industrial activities are not widespread. Generally, agricultural activities in the Alps are restricted to extensive livestock farming (predominately cows and sheep) and small-scale – predominately rainfed – crop farming. Within the southern Alpine belt, which is more influenced by the Mediterranean climate, part of the small-scale crop farming is irrigated. According to the climate change projections, part of the rainfed agriculture will have to shift to irrigated agriculture and irrigation water requirements will increase during certain periods of the year (Wriedt *et al.* 2009). However, with the right investments, for example altering cultivation intensity and crop choice,

sustainable land use and irrigation management (EEA 2009), these problems can be solved.

Hydropower is an important energy source in the Alps and is especially important for supplying peak demands. The installed hydropower capacity in the Alps is estimated to vary between more than 400 MW in Germany and Slovenia, more than 2,900 MW in France, Italy and Austria and more than 11,000 MW in Switzerland (EEA 2009). The predicted change in seasonality of river flows will have an impact on the productivity of installed plants. For Austria, a reduction in electricity generation from hydropower stations of between 6 and 15% by the end of this century is projected (Stanzel & Nachtnebel 2010). In Switzerland, where hydropower provides about 75% of consumed electricity – of which around 60% is produced from storage reservoirs – a reduction in electricity production by the end of this century is also forecasted (Schaeffli *et al.* 2007).

Tourism is one of the most important industries in the Alps, and especially winter tourism. Owing to less natural snow reliability as a result of climate change, on the one hand, and the demand for higher standards by winter tourists, on the other hand, the production of artificial snow in ski resorts has increased substantially during the last 20 years and is likely to increase further in future. Water for snowmaking is generally taken from streams and springs. Especially during the base snowmaking phase at the beginning of winter, water requirements are very high. Improvement snowmaking during the rest of the season also requires substantial amounts of water. However, with the right investments – the implementation of reservoirs – regional water availability is sufficient to meet snowmaking water demands (Vanham *et al.* 2009b).

IMPLICATIONS FOR WATER MANAGEMENT IN THE WATER-DEPENDENT LOWLANDS OF THE ALPS

The impact of the change in seasonal water availability on the water management sector in the lowlands of the four assessed river basins is much more profound than in the Alps; water demands are much higher because of the higher population densities and the concentration of big industrial regions and vast plains with intensive agriculture. In particular, the decrease in water availability from late

spring to autumn and the projected increase of drought period occurrences have important consequences for the water sector in the lowlands. During winter the increase in water availability may lead to flood risks, which may threaten the physical infrastructure of water companies. Moreover, the high turbidities of flood water and the associated increase in pollution levels pose challenges to the water treatment processes of drinking water companies.

The lowlands of the Rhine basin are densely populated and heavily industrialised, and the River Rhine has the highest traffic density in Europe as an inland waterway (Middelkoop *et al.* 2001). There is a huge economic interest in an unhampered water connection between the harbour of Rotterdam and the industrial regions in Germany. Similar to the Rhine, the Danube and Rhone fulfil an important function in navigation, water supply and hydroelectricity. In the Rhone basin about 69% of the water abstracted is used for cooling purposes (EEA 2009). The Rhone also contributes water to irrigation areas in its basin. Irrigation areas in the downstream part of the Danube basin are fed by Danube water. The Po basin accounts for 40% of Italy's GDP. It is home to 37% of the country's industry, providing 46% of jobs, about 55% of livestock and 35% of the country's agricultural production. Irrigated agriculture is responsible for 46% of total water use: for example, rice – a highly water-consuming crop – is grown as one of the major crops.

An event that gives a unique opportunity to observe the future situation in the lowlands of these four river basins was the summer heat wave of 2003 in Europe. This extreme climatic situation resembles simulations by regional climate models of summer temperatures in the latter part of the 21st century under the A2 scenario (Beniston & Diaz 2004). According to Schär *et al.* (2004), at the end of this century (2071–2100) every second summer could be as hot (or even hotter) and as dry (or even drier) as the summer of 2003. Therefore the well-documented event of the summer of 2003 represents a unique chance to assess the impact of future climatic conditions. Although modelled climate projections are subject to high uncertainty, a comparison of such projections with the 2003 event can give valuable information. A severe heat wave and accompanying drought over large parts of Europe in 2003 extended from June to August, raising summer temperatures by 3–5 °C in most of southern and central Europe and lowering precipitation substantially.

Many major rivers (e.g. the Po, Rhine, Rhone and Danube) were at record low levels, resulting in disruption of inland navigation, irrigation and power plant cooling (Beniston & Diaz 2004). The extreme glacier melt in the Alps prevented even lower flows of the Danube and Rhine rivers (Fink *et al.* 2004; Zappa & Kan 2007).

During July, August and September the Rhine was at record low levels. Islands formed in the river and inland navigation was reduced significantly. Transports had to be partly shifted to railways and roads. Water temperatures increased, therefore restricting its use as a coolant for power plants. Several power plants had to reduce their production because they could not divert enough cooling water either physically or legally from the rivers. For example, the German nuclear power facility Isar 1 reduced its power generation by about 40% (Fink *et al.* 2004). No overall energy shortage arose, but the prices for electricity increased. Tennesse, the manager of the high voltage grid in the Netherlands, placed its cooling water restriction on red status because of water temperatures above 26 °C at the Lobith gauge on the Rhine. However, no shortages in drinking water supplies occurred in Germany because there had been sufficient replenishment of groundwater resources and reservoirs in the anomalously wet October 2002 to January 2003 period (Fink *et al.* 2004). The increase in water temperatures also affected the quality of surface and groundwater bodies. The decline in water quality during the summer of 2003 is both related to the high water temperatures and to low river discharges (limited dilution of the chemical load from point sources) (Zwolsman & van Bokhoven 2007). In the Rhine estuary in the Netherlands the sea penetrated further inland, leading to groundwater and surface water salinisation. For a densely populated country such as the Netherlands, this posed major threats to water supply for drinking water, industrial production and agriculture.

At the end of the summer 2003, the water level of the Danube fell to the lowest levels in over a century, stranding ships and barges from southern Germany to the Romanian lowlands. The hydropower plants along the Danube and its tributaries produced less electricity than normal. Romania's Cernavoda nuclear power plant, which draws coolant water from the Danube, was forced to shut down for almost a month (EEA 2009).

In the Rhone basin the heat wave spelled trouble for different nuclear reactors, many of which are cooled by river water. The nuclear power plants of Saint-Alban (Isère), Cruas (Ardèche), Tricastin (Drôme) and Bugey (Ain) continued functioning, although the upper legal limits were exceeded (UNEP 2004). Moreover, demand for electricity peaked as the population turned up air-conditioning and refrigerators, but nuclear power stations, which generate around 75% of France's electricity, operated at a much reduced capacity. In order to conserve energy for the nation, France (Europe's main electricity exporter) cut its power exports by more than half.

Big power plants on the River Po lacked the water needed to cool their turbines, and Italy suffered power blackouts when public demand overloaded the system. Along certain stretches of the Po river, the water level fell more than 8 m below normal, bringing all water traffic to a standstill. Decisions had to be made whether to allocate water for energy production or for agricultural irrigation. The period was characterised by salt water intrusion in the Po delta (Alpine Convention 2009).

OVERVIEW OF EXPECTED FUTURE IMPACTS

In this review the importance of mountain water for the lowlands of the Rhine, Danube, Rhone and Po river basins is shown. Climate change projections indicate that both snow cover duration and volume will reduce substantially in future, resulting in a shift in mountain hydrological regimes with an important impact on downstream water resources availability. Forecasts include an increase in winter discharge, a decrease in summer discharge, increases in the frequency and height of peak flows, and longer and more frequent periods of low flow during summer. In the Alps different water demand stakeholders of the water sector are affected. The impact is dependent on the particular region of the Alps, as conditions can differ profoundly (Viviroli *et al.* 2011). With the right investments and policies (Hohenwallner *et al.* 2011) these problems can be generally overcome. Owing to low population densities, water availability remains high with respect to total water demands. In the lowlands, however, impacts are more severe because of the high population densities and the demands from

economically important industrial regions and vast agricultural plains. A reduction in water availability for industry, agriculture and domestic use during the season of peak demand is forecasted. A decrease in annual hydropower generation and an increase in the number of low-flow days affecting shipping activities will have important socio-economic implications.

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