ACQWA

Assessing Climate impacts on the Quantity and quality of WAter

Deliverable D.Policy.5a
Consolidated scientific findings of key impacts of climate change on water resources, aquatic ecosystems and sectoral users
Month 43

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Submitted: 14.04.2012; Validated: 27.04.2012

The following report provides an overview of the consolidated scientific findings from the science outputs of ACQWA as available up to month 43. This will be further developed in months 48–54, as further science deliverables are completed and scientific conclusions become available.

1. Introduction

The Alps in general and Switzerland in particular have in the past been referred to as “the water tower of Europe” (Mountain Agenda, 1998), as they are the source region for many rivers that flow through Western and Central Europe (e.g., the Rhine and the Inn rivers and their tributaries), as well as towards the Mediterranean Sea (e.g., the Rhone and Ticino rivers). Over the past century, numerous signs of climate-driven changes in the Alps have been observed, as exemplified for example by the general retreat of mountain glaciers (Paul et al., 2007), subtle shifts in species composition within alpine plant communities (e.g., Keller et al., 2005), or the consequences of poor snow conditions on revenue from winter tourism during an increasing number of winters since the 1980s (OECD, 2006). Recorded temperatures have risen by up to 2°C since 1900 particularly at high elevations, a rate that is roughly three times the global-average 20th century warming (Beniston, 2004). In coming decades, any substantial changes in the mountain snowpack will have a significant impact on the surface runoff in many river basins. The direct and indirect impacts of a warming climate will affect key economic sectors such as tourism, hydropower, and agriculture. Changes in the frequency of extreme events, notably heavy precipitation, floods and droughts will have an impact on the vulnerability of infrastructure and a range of economic sectors and services, and as a consequence on the insurance industry that will be confronted to more severe natural disasters.

This paper will provide a brief overview of future changes in climate that are projected by a range of climate models that have been developed and applied to the alpine region in EU projects such as FP5 “PRUDENCE” (http://prudence.dmi.dk), FP6 “ENSEMBLES” (http://ensembles-eu.metoffice.com/). The objective of the ACQWA project (www.acqwa.ch), a Large Integrated Project under the EC Framework Programme 7 coordinated by the University of Geneva, is to assess the vulnerability of water resources in mountain regions where snow and ice are a major component of the hydrological cycle. The quantity, seasonality, and possibly also the quality of water will in coming decades be intimately linked to changing snow and ice in the mountains. The project is implementing a suite of numerical models to help understand the links between climate, snow and ice, vegetation, and hydrology, with an aim at predicting the evolution of these systems by the middle of the current century. A further objective of ACQWA is to assess the potential impacts of changing water regimes on major water-dependent economic sectors such as energy, agriculture, and tourism for example, with a view of identifying possible rivalries among sectors that are likely to increasingly compete for a dwindling resource. The overall aim of this part of the project is to see whether such conflicts could be minimized through improved water governance. Finally, investigations focus not only on mean changes but also on shifts in extremes of precipitation and the consequent hydrogeomorphic responses that can add a further burden on the capacity of society to respond and adapt to the collateral effects of extreme events.

The paper will go on to address issues related to changing natural hazards in the alpine part of the Rhone catchment from the Rhone glacier to the Lake of Geneva and how these may contribute to disrupting water quality and quantity. This catchment is one of the key case-study areas of the ACQWA project in the European Alps, because of the availability of data that enable robust testing of the modelling approaches and quantification of the socio-economic impacts, both in a historical and a future perspective. Other case-study areas in the ACQWA project include the Po basin in Italy as an example of a river with a more Mediterranean flow regime, the Aconcagua River in Chile (as a possible reflection today of future climate and hydrological regimes in the Alps in coming decades), and Kyrgyzstan (where receding glaciers and associated surface runoff surpluses could, over a number of decades, represent an opportunity to develop hydropower infrastructure and sell energy to neighbouring countries).

Finally, the paper will discuss questions related to current and future water governance in the region, and whether water-related policies are sufficiently robust today to cope with what may be rapid changes in water availability and water use in coming decades, and to resolve possible rivalries between economic sectors that may be increasingly confronted with problems of water availability at critical times of the year.

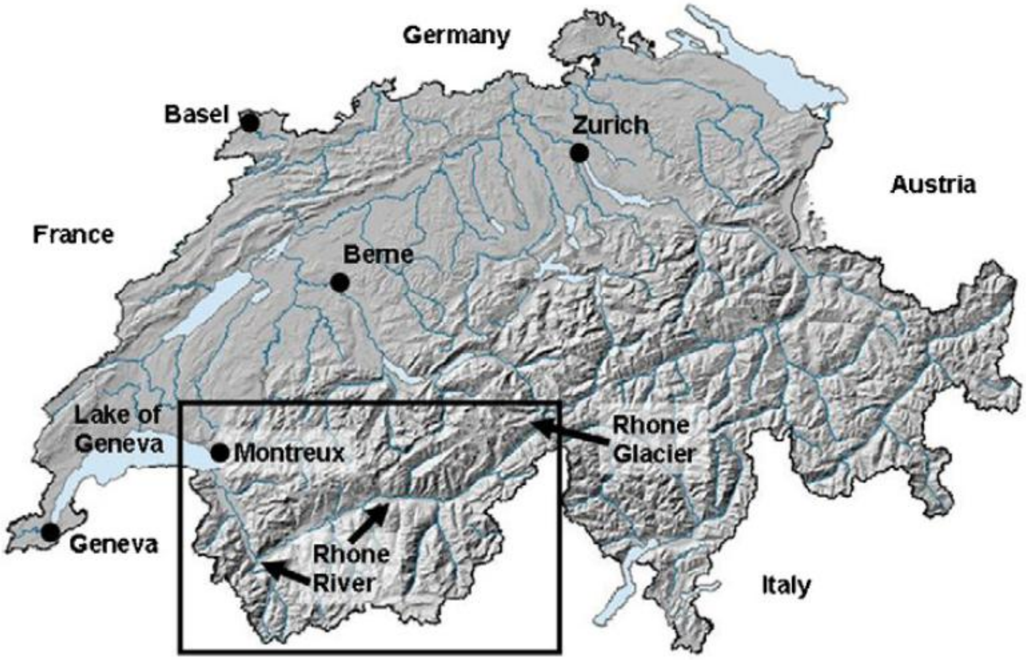

Figure 1: Map of Switzerland showing the geographical location of the upper course of the Rhone River, from its source in the Rhone Glacier to the Lake of Geneva near Montreux, Switzerland.

The Rhone River, although small by many standards, is the largest river feeding freshwater into the Mediterranean after the Nile. Figure 1 provides an overview map of the catchment region in the Swiss part of its basin. The source of the river is the Rhone Glacier, in the Swiss canton of Valais (Wallis), in a region of elevated peaks exceeding 4,000 m in the central part of the Alps. The Rhone flows into the Lake of Geneva and crosses into France to the west of the city of Geneva. The total surface area of the Rhone basin (Switzerland and France) is 95,500 km^2, and the Swiss segment is roughly 10,100 km^2. The total length of the river is over 800 km from the Rhone Glacier to the Rhone Delta in the Camargue region near Marseille (261 km within Switzerland), and is bordered by a total of 16 million persons (1.2 million in Switzerland). The major uses of Rhone River waters include hydropower in the Alps, water for cooling of thermal and nuclear power stations in France, irrigated agriculture, recreation, and navigation (from the Mediterranean to Lyon, essentially). Average annual discharge as the Rhone enters into the Lake of Geneva is about 180 m^3/s, with late spring/early summer discharge exceeding 600 m^3/s during periods of strongest snowmelt, while winter discharge is less than 100 m^3/s. During flood events, discharge can exceed 1,000 m^3/s.

2. Future climatic trends in the Swiss Alps

Regional Climate Model (RCM) simulations suggest that most of Europe will warm in all seasons, but summers are likely to warm the most in many parts of the continent as a result of the positive feedback effects of increasingly dry soils, particularly in southern and central Europe (Beniston et al., 2007). In Northern Europe, there is likely to be more precipitation on average than under current climate, while in a large band stretching from France to the Black Sea by as much as 40%. Simultaneously, RCM results also point to a strong increase of short-lived but very intense precipitation events in certain regions that are already prone to such hazards today, for example the river systems of central Europe (Christensen and Christensen, 2003). The risk of flood hazards in many parts of Europe is likely to increase as a consequence of changes in continental-scale climate, because of higher overall precipitation in northern Europe and/or an enhancement of short-lived but very high intensity events.

In the Swiss Alps, RCM results show fairly consistent trends in both temperature and precipitation by 2100, whatever the emissions scenario considered. Winter temperature increase may be close to 4°C in winter and more than 6°C in summer compared to the 1961-1990 baseline climate (Beniston, 2009). Most models agree on the sign of change in seasonal precipitation in the Alps if not on the changes in amount (Beniston, 2006). Increases of 15-35% in wintertime precipitation and significantly-curtailed summertime rainfall (20-40% reductions may be expected over coming decades, according to the model used.

Snow is an essential component of mountain hydrological systems, and any changes in the amount of snow, its duration, and the timing of snow-melt can have long-lasting environmental and economic consequences. Snow determines the timing of peak river discharge during the melting of the snowpack in spring and, in many instances, maintains river flows even during warm and dry summer periods. The two principal determinants of snow and ice are temperature and precipitation; as climate warms and moisture regimes change, so will snow amount and duration. In mountain regions, an average rise of 1°C is accompanied by a general rise of about 150 m in the altitude of the snowline (Haeberli and Beniston, 1998).

In a scenario climate, warmer conditions associated with enhanced winter precipitation in the Alps are likely to lead to more abundant snowfall in the higher reaches of the mountains, but much reduced snow at lower levels where precipitation is more likely to fall in the form of rain. Beniston et al. (2003) have shown that the crossover level where snow becomes more abundant under milder conditions is located between 1,700 and 2,000 m above sea level. In terms of snow volume, which is a key variable for assessing peak flow from snow-melt in river systems originating in the Alps, the same paper has estimated that winters under an IPCC A2 emissions scenario (Nakicenovic et al., 2000) will experience 90% reductions in snow volume below 1000 m asl and 50-60% at 2000 m asl. Above 2000 m, even if the total snow accumulation is greater as a result of enhanced winter precipitation, the volume of snow will be lower because snow will accumulate on surface areas that diminish rapidly with altitude.

In terms of ice cover, the glaciers in Switzerland and its alpine neighbours have lost between 30 and 40% of their surface area and about half of their volume since 1900 (Paul et al., 2007). Empirical and energy-balance models indicate that 50–90% of existing mountain glacier mass could disappear by 2100 according to the intensity of future greenhouse gas emissions (Haeberli and Beniston, 1998). For most mountain glaciers in the temperate parts of the world, there exists a close linear relationship between the equilibrium line altitude of the glacier and the precipitation and temperature controls on glacier mass. Farinotti et al. (2009) estimate that in order to maintain the equilibrium line altitude of a glacier, roughly 300 mm of additional precipitation per degree of warming would be necessary. Projections from regional climate models suggest that in the alpine region, warming will be accompanied by an average reduction of annual precipitation, thereby implying rapidly waning glaciers until they find perhaps another equilibrium at much higher elevations and with substantially reduced volume and surface area; some may disappear entirely if the equilibrium line altitude is positioned above that of the glacier catchment area.

3. Impacts on water regimes

On average, Switzerland receives close to 1,500 mm of precipitation per year, of which one-third is lost through evaporation and close to two-thirds contributes to surface runoff; a small fraction is stored in lakes, dams, and serves to recharge groundwater reserves. Within a 30-km radius in the Gotthard region of central Switzerland, surface runoff feeds river systems that flow into the North Sea (the Rhine river basin, representing about two-thirds of total water exported from Switzerland), the Mediterranean (the Rhone river basin, with about 18% of water exports), the Adriatic (the Ticino that converges with the Po river in Italy and represents 10% of runoff from Switzerland) and the Black Sea (via the Inn that converges with the Danube in Germany, and accounts for about 5% of surface runoff), as described in the Swiss Hydrological Atlas (FOEN, 2007). The key point here is that any change in precipitation regimes, snowpack depth and duration, and the speed of glacier retreat in this very small part of the Alps will have important impacts not only for the mountain valleys but also for the populated lowland regions of Germany, south-eastern France, northern Italy, and Central and Eastern Europe that depend on alpine water resources for an important part of their water supply.

Alpine water resources are strongly influenced by mountain climates that govern soil moisture, groundwater recharge, evaporation and runoff. The Rhone river discharges are controlled by evaporation, precipitation, storage of water in artificial reservoirs, and melt water from snow and ice. Precipitation throughout the year, and snow and ice melt waters from May to October provide input to the river basin; in addition, hydro-power utilities release water into the catchments and tributaries of the Rhone during the winter half-year in order to generate power during the peak energy demand period of the winter. Water is locked in the winter snow-pack on average from November to May, while evaporation reaches a maximum during the summer months. Dams retain a small part of snow-melt and precipitation during the summer months and store this water to prepare for supplying energy later in the year; this storage removes water from the system that would otherwise contribute directly to runoff.

Because precipitation is fairly evenly distributed throughout the year and storage of water in dams represents a small fraction of the total amounts of water involved, the most important seasonal signal in terms of runoff is determined by the alpine snowpack, in particular the timing of snowmelt and the amount of melt water which is a function of the quantity of snow accumulated during the preceding winter.

In a scenario climate, runoff by 2100 is seen to change in seasonality and amount compared to current climate (Figure 2). Peak discharge takes place 2-3 months earlier in the year, and maximum flow is reduced because of the smaller contributions by the melting of a less voluminous snow-pack. The average 30-year flow shown in this figure shows a modest rise in discharge during the summer, as a result of summertime convective activity that could still occur despite a strong reduction in average summer rainfall projected by RCMs. Even during summers with convective precipitation, however, the reduction in discharge compared to the baseline conditions ranges from 50 to 75% on average. The gray shading gives an estimated range of uncertainty of the results, according to the amount of snow and the timing of spring melt, the estimated remaining glacier mass, and shifts in seasonal precipitation. Runoff towards the middle of the 21st century is likely to lie within the dotted lines; this part of the graph remains largely speculative, however, but it is expected that more precise projections will be available within the next 1-2 years thanks to results emerging from the ACQWA project.

Because of the large interannual variability of runoff, as a result of the sharply curtailed glacier mass in the mountains and possibly long and dry summers, the volume of summertime glacier melt waters may no longer be sufficient to feed water into river catchments at a time of the year when precipitation amounts are low and the snowpack has already melted earlier in the year. Consequently, in some years, the Rhone may dry up partially or completely towards the end of the summer and into the early fall. The future characteristics of runoff shown in this figure are more typical of rivers that are currently found in the Mediterranean parts of the Alps, as in the French Provence region (for example the Durance River) and in parts of the Italian-facing slopes of the alpine arc, such as the Maggia River in Ticino or the Po catchment in Italy (e.g., Rabuffetti et al., 2008).

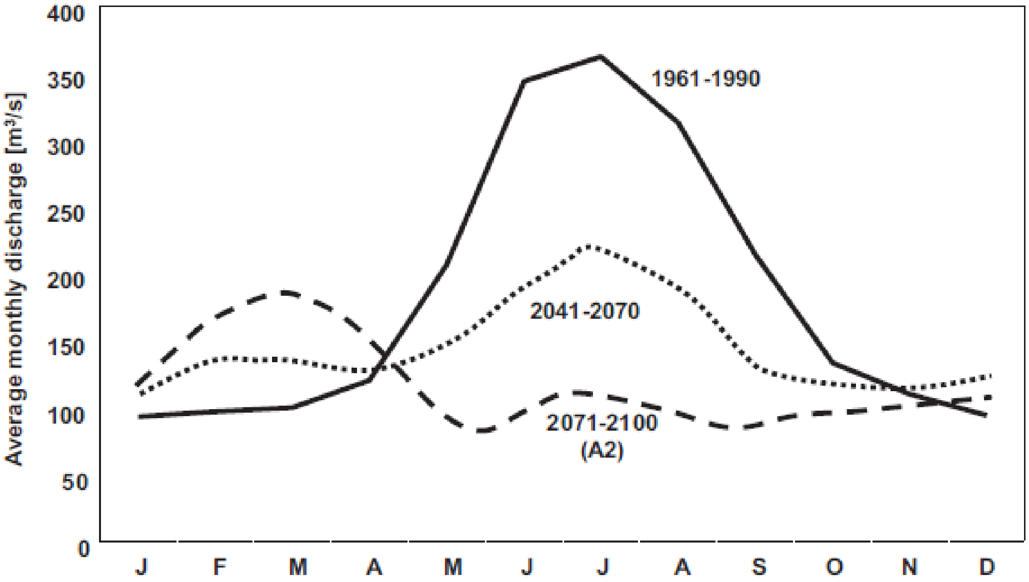

Figure 2: Changes in monthly discharge of the Rhone River close to its mouth in the Lake of Geneva, near Montreux, from current (1961-1990) to future (2041-2070, and 2071-2100, IPCC A2 emissions scenario). The gray shading gives the possible range of discharge, according to the timing and volume of snow melt, estimates of glacier retreat, and shifts in seasonal precipitation.

4. Changing hazards and risks in the alpine part of the Rhone River catchment

Changes in temperature, precipitation totals, rainfall intensity and soil moisture conditions are likely to influence the frequency and magnitude of geomorphic and hydrological processes as well as associated hazards and risks (Borgatti and Soldati, 2010; Goudie, 2010). As the severity of climate change will vary spatially, potential impacts will vary as well. For example, warming in various parts of the European Alps has been up to 3 times the amplitude of the global-average warming since 1900 (Beniston, 2004, 2005). In addition, precipitation change exhibits both latitudinal and longitudinal dependencies that are projected to amplify in a warmer world and to be modulated by local forcings (e.g., topography, land use). As a consequence, alpine glaciers are likely to melt at higher rates, permafrost is likely to thaw and retreat, and floods and droughts are thought to become more frequent at a global level (IPCC, 2007). Based on RCM data (Christensen and Christensen, 2003; Graham et al., 2007), future summers are likely to occasionally favour very severe precipitation episodes that result in catastrophic flooding, despite a general trend towards drier summer conditions. Although the frequency of extreme floods in central Europe did not increase in frequency as compared to past centuries (Mudelsee et al., 2003), it seems likely that unusually large floods beyond historical experience will occur in a future greenhouse climate (Milly et al., 2008).

Debris flows, rockfalls and landslides are natural, multi-dimensional and non-linear dynamical systems with a complex behaviour in space and time (Brunsden, 1999). Their evolution is strongly connected with other processes (e.g., fluvial or periglacial), and is sensitive to both inherited and present controls. Climate is coupled with mass-movement processes through the highly non-linear soil-water system and no unique relationships exist between climatic conditions and the occurrence of mass movements. Nevertheless, it can be assumed that a connection between climate (i.e. hydrological balance) and mass-movement (in-) activity exists at daily to millennial timescales. An increase in meteorological extremes (Beniston et al., 2007) is therefore likely to result in increased frequency and/or magnitude of mass movements (Crozier and Glade, 1999). In addition, a rise in the lower permafrost boundary as well as decreasing permafrost thickness may enhance the risk of large, deep-seated landslides (Harris et al., 2009). A number of large rockfalls from steep slopes undergoing thawing have been reported in the recent past (Geertsema et al., 2006; Chiarle et al., 2007; Huggel, 2009). As a result, more instability is likely to occur as a consequence of the increasing number of extreme meteorological events or by increasing cumulative rainfall, infiltration and runoff (Borgatti and Soldati, in press), but impacts might be highly variable within or between different regions of the Alps (Goudie, 1996).

In the Rhone catchment, the occurrence of past and potential future mass movements is currently being investigated with dendrogeomorphic techniques, i.e. through the study of growth-ring records of trees that have been affected by past disasters (Stoffel et al., 2010). A majority of mass-movement processes occurs in the lateral valleys which are characterized by high-elevation peaks (up to 4634 m asl) and steep gradients between the summits and the valley floors. Rockfalls are very common and primarily triggered by freeze-thaw cycles in spring (Stoffel et al., 2005a), but heavy rainfalls have been reported as a cause of larger events as well (Schneuwly and Stoffel, 2008). The impacts of changing climate are most visible at higher altitudes dominated by permafrost environments where more and larger events were reported during past (AD 1720) and recent heat waves (Gruber et al., 2004; Stoffel et al., 2005b). The retreat of glaciers and the melting of permafrost, along with a potential increase in the frequency and magnitude of heavy rainfall events in spring and fall, are likely to locally exacerbate the number (and possible also the size) of rockfalls in the future.

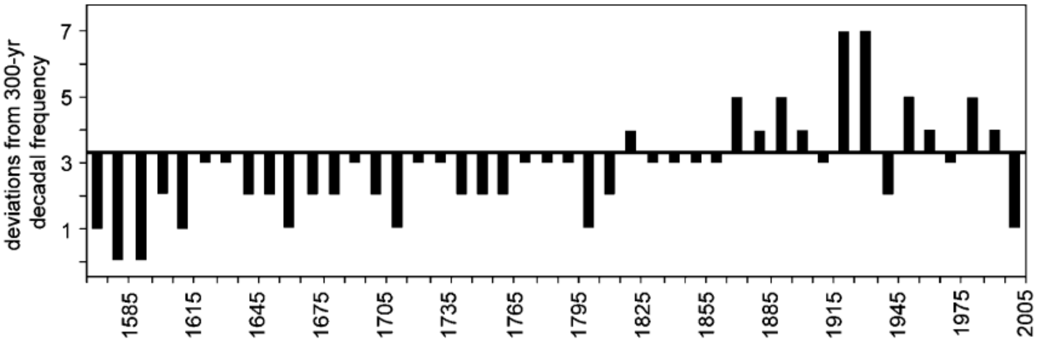

Figure 3: Tree-ring based reconstruction of debris flow activity in a torrent of the Valais Alps (Ritigraben, Grächen) extending back to AD 1566 and containing 124 events. Past activity is given as 10-yr frequencies and data are presented as variations from the mean decadal frequency of debris flows of the last 300 years (AD 1706–2005). Note the sharp decrease of debris-flow activity in the recent past.

Debris-flow channels are widespread within the Rhone catchment and have caused significant damage to transportation corridors, infrastructure and people during intense advective rainfall events in the recent past (Schmocker-Fackel and Naef, 2010). Time series of debris flows from the Zermatt valley indicate that the frequency of events increased as a result of warming climate after the end of the Little Ice Age (Stoffel and Beniston, 2006) and that debris-flow activity culminated in the first third of the 20th century because of a series of warm-wet summers (Stoffel et al., 2008). Figure 3 shows that in the recent past, however, debris flows were less frequently triggered from these high-elevation, permafrost dominated catchments (Stoffel and Beniston, 2006; Bollschweiler and Stoffel, 2010), despite the fact that permafrost wasting delivered larger amounts of debris to the release areas of these torrents (Lugon and Stoffel, 2010). This decrease in debris-flow frequency seems to reflect the decreasing number of summer rainfalls capable of triggering debris flows since the late 1980s (Stoffel et al., in press) and somehow blurs the fact that future debris flows are likely to have larger magnitudes and that related impacts for people and infrastructure are very likely to be beyond historical experience (Lugon and Stoffel, 2010; Stoffel, 2010).

5. Coping with uncertainty: the role of water governance in responding to future risks, hazards and stresses.

The previous sections elucidate the extent to which the speed and magnitude of change in future climatic and hydrogeomorphic conditions pose potential risks that lie beyond the human experience and therefore the boundaries of coping ranges. Effective water governance is seen as being at the heart of present and future water challenges, and is considered crucial for building adaptive capacity (Nelson et al., 2007; Brooks et al., 2005; UNECE, 2009): the ability to prepare for and cope with stress and uncertainty from future climatic change variability and stress (Adger et al, 2007; Smit and Wandel, 2006). As part of the ACQWA project, an investigation of the water governance regime is taking place in the upper Rhone catchment area of the Valais, including an exploration of its capacity to cope with impacts from climate change (as detailed in Sections 2–4). In terms of water resources management and provision in the Valais region, a highly devolved and complex multi layered governance system has been developed (Hill, 2010), recently overlaying economic priorities with environmental provisions.

The legal framework for water is defined through different, sectorally focused acts at the federal level, including the Water Protection Act (WPA), cantonal level (Petitpierre, 2009) as well as local level regulations and agreements among public and private actors (Hill, 2010). In the Valais added complexity exists because sovereignty over water resides with the canton for the Rhone, at the municipal level for the tributaries and with private water rights holders. In addition, 80-year legal concessions granted to the hydropower operators predated environmental considerations, which continue to cause tensions between environmentalists, fishermen and those using or granting water for power generation (Bonzi, 2009; FOEN, 2010). Despite a wealth of local and cantonal rules governing sectoral and local uses, today there are few, if any, overarching principles for user conflicts. The institutional framework remains highly sectoral, both in the legal framework and the organizations that must implement it.

In Valais past extremes have been used as a context in which to explore the governance system's ability to adapt to future shocks. Flooding events (1993 and 2000) and periods of stress (2003 heat wave, peak periods of demand) are used to illustrate how adaptive the system might be to events that might become more recurrent or intense in the future. The management of different extreme events in Valais suggests that while water managers may be responsive to increasing heavy precipitation events, historic adaptive strategies to the dry conditions in Valais may no longer be sufficient to different speeds and scales of future change (Hill, 2012). The difference in reaction and management to events within the flooding and stress contexts is presented in Table 1. In addition the table presents potential inferences drawn from this for the ability of the different elements of the governance system to cope with future impacts from climate change.

During the major heat wave in 2003 and other warm summers, increased runoff from glacial melt has so far served to buffer any issues from the lack of precipitation for most of the region, but some municipalities in the northern, less glaciated region have reported increasing periods of stress (Hill, 2010). In general, the threat from climate change impacts on water quantity is perceived as a distant one. More pressing points of tension are the legal requirements for residual flows and reductions in hydro-peaking which come into effect in 2012 (FOEN, 2010) requiring hydropower operators to release more water for environmental flows; an interesting attempt to increase the resilience of the waterways.

Contrastingly, an increase in volume of water to be managed in extreme events (after a relatively stable period between the 1920s and early 1980s), has led to a considerable shift in federal and cantonal watercourse policy. Watercourse management had been highly dominated by notions of steady state resource management, an unyielding belief in the infallibility of engineers' calculations and the concept of building absolute security through deepening the river and strengthening the dykes. Earlier flood prevention policies created a noxious situation of increased vulnerability to recent increases in the quantities of flood water. The new flood concept, as being implemented through the Third Rhone Correction (TRC; www.valais.ch/rhone), however suggests a shift in mindset at federal and cantonal levels (Table 1) in their attempt to embrace change and uncertainty as basic features of the system.

	Flooding Watercourse Management	**Water Shortage** Water Provision
Event Development	Recent intensification of amount of water during events since the early 1990s (after stable period 1920-1980)	Rain shadow and long term peaks of demand – increased glacial melt buffers lack of precipitation
Institutional Coping Tools	Networks between hydropower operators and canton/municipalities (MINERVE) Networks of crisis groups Modelling and observation Networks Public information for sensitization Financial incentives to follow federal guidelines	Common property resource regimes (informal rules) governing irrigation waters through user groups and canals (*Suonen/Bisses*) Legal provisions prioritizing certain amounts of historic flow rights to agricultural users Local Agreements/regulation for use transference/priority setting
Technical Coping Tools	Development of extra storage in reservoirs (MINERVE) Implementation of emergency evacuation channels (TRC) Increased space for the Rhone (TRC) Introduction of environmental flows (WPA) Efforts to reduce impacts from hydro-peaking (WPA)	Different users rely on different sources Diversification of uses: Irrigation canals from the glacier – farmers New storage lakes –tourism Groundwater –drinking water Melt waters and river flow - hydropower Increased integration and connectivity of different communities
Potential Tipping Points	Increase in altitude of the snow line during heavy precipitation events, leading to an augmentation in the volume of river flow.	Reduced contribution to run off from glacial melt and snow pack decreasing the quantity of run off during the dry summer season.
Future Outlook / Preparedness for change	Anticipating future shocks Organising for future threats - attempting to be adaptable to future climate Introducing new concepts (TRC and WPA) for flexible and robust approaches	Adaptive local processes (community based adaptations) for local level periods of peak/stress. New shocks (e.g. impacts in Section 2-3) at different scales are not under consideration.
Key Issues	Reactive adaptation to past extremes leading to proactive capacity building for future ability to cope. Stakeholder opposition to the strategies for integrating of environmental and climate considerations into the governance approach. Difficulty in implementing federal provisions which aim to foster ecological resilience and reduce damage from climate impacts.	Knowledge that future shocks from climate change impacts may occur, but no sense of urgency or strategy to manage potential rivalries that will arise out of the situation. Sectoral based networks Lack of rules and institutions to manage rivalries beyond the municipal/sectoral level. Long term inflexible use rights for water (e.g. 80–100 year concession period for hydropower)
Adaptive Priorities	In response to recent extremes, flood policy planned to be adaptive and robust. Continue to build up the recognition of non-stationarity in the system (building redundancy through residual risk concept) Foster links with other sectors to build awareness around adaptiveness to climate impacts Integration between flooding / hazards planning concepts and urban planning guidelines	Need to generate pro-active adaptive capacity Initiate the integration of climate change into planning processes (e.g. renewal of hydropower provisions in next 10-15 years; infrastructure development) Improve communication and networks between a wider range of stakeholder groups, rather than the dominant sector specific framework. Flexible and iterative processes to integrate new knowledge into legal provisions (e.g. seasonal based legal provisions for use priorities)

Table 1: Differences in response to extremes within the flood and water shortage context, implications for future capacity to cope, and potential solutions to remedy the gaps identified.

6. Conclusions

Though water is present in ample quantity at the Earth's surface, the supply of water is limited and governed by the renewal processes associated with the global hydrological cycle. Mountains tend to intercept substantial amounts of water in the form of snow and rain from the predominant large-scale atmospheric flows. This water ultimately flows out as rivers, forming the most accessible freshwater supply to the more densely populated plains downstream of the mountains. Mountains are the source region for over 50% of the globe’s rivers, and clearly the impacts of climatic change on hydrology will have repercussions along the entire courses of these rivers that supply water for domestic, agricultural, energy and industrial purposes.

Water resources for lowland regions are influenced by mountain climates and vegetation; snow feeds into the hydrological basins and acts as a control on the timing of water runoff in the spring and summer months. Hydrological systems are also controlled by soil moisture, which largely determines the distribution of ecosystems, groundwater recharge, and runoff; the latter two factors sustain river flow and can lead to floods. Any changes in these fundamental controls may have major impacts on the physical determinants for surface runoff.

The Rhone River, even though modest in size compared to other river systems, is no exception to this rule. This paper has highlighted the fact that there are likely to be profound shifts in the availability of water according to season as climatic change accelerates over coming decades, with a transition to surface flow regimes that may resemble those of rivers flowing in the more Mediterranean reaches of the Alps. Changes will be accompanied by altered patterns of natural hazards that are capable of perturbing many sectors where water is a key resource.

These physical changes represent a challenge to water governance strategies. The ACQWA project, by investigating through an end-to-end strategy the impacts of climatic change on physical and socio-economic systems in the Rhone River basin, aims to identify the key problems that will be faced in terms of future water policies.

The shock of major flooding events in the 1990s and early 2000s caused a shift in the framing of flood management policy, to better account for inherent uncertainty and non-stationary conditions. The key issue for policy makers is how this learning process can be replicated so that water managers focus more heavily on adaptive processes in sectors or regions where future stresses may go beyond historical experience. One step towards realizing how to achieve this is to directly link up physical impact information with vulnerability and adaptive capacity assessments at local to regional levels, as the ACQWA project is attempting over the next few years. Another step could be for regional and local policy makers to better share lessons learnt and planning practices across different regions as well as aspects of water management.

The increased integration of uncertainty, and worst-case scenario planning could also improve the integration of longer term climate related issues into planning at local to regional scales, which may have been resistant or apathetic to contemplating climate impacts in planning decisions. The wider discussion of how to manage for uncertainty and worst case scenarios could also help reduce levels of societal resistance to new strategies, which require land or water to be set aside for a new stakeholder, namely the environment, in order to build the ecological resilience so important for buffering projected impacts from climate change. Another key challenge for policy makers is the need to balance flexibility with requisite predictability in legal frameworks, so that opportunities to face future threats are not handcuffed by policy decisions taken in the next 10 to 15 years, as they were from decisions taken in the last century.

This paper has addressed a number of issues related to water availability and use that are significant, especially because of the growing interconnection among regions and economic and social sectors. By the time of completion of the ACQWA project at the end of 2013, it is expected that novel answers to social and economic issues will have emerged. Among these issues, one can identify changes in social arrangements among mountain populations and their downstream neighbours, energy production in regions where water is underused as a means of helping abate greenhouse-gas emissions, and environmental issues such as the future evolution of water supply for use in the domestic, tourism, or agricultural sectors.

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