Assessing Climate impacts on the Quantity and quality of WAter

Deliverable D.Policy.1: Water distribution and allocation among sectors, vulnerabilities and policy alternatives – month 59

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1. Key challenges and vulnerabilities in relation to climate change impacts and uncertainty

Shifting climate trends have already been notably observed in mountain zones, while future warming patterns are set to affect mountain regions more acutely, thus leaving their sensitive ecosystems, communities and economies highly exposed to changing climatological and hydrological contexts (Beniston et al., 2011; Gobiet et al., subm.). Effective water governance and management is seen as being at the heart of present and future water challenges, and is considered crucial for building adaptive capacity to be resilient to the impacts of climate change (Nelson et al., 2007). As climate change impacts are increasingly observed, existing challenges within policy and legislative frameworks are being exacerbated by the rate of change within the physical system (Ostrom, 2007). Since policy makers are focusing more and more on climate change adaptation and adaptability (FOEN, 2012), current challenges in the governance context need to be better understood, contextualised in terms of future climate patterns, and finally alleviated.

Scientific efforts have focussed heavily on the reduction of uncertainty through enhanced data collection and modelling (Schneider and Kuntz-Duriseti, 2002). The EU-FP7 ACQWA project aimed to develop climate information downscaled to temporal and spatial scales that are more useful to the challenges decision makers face (Beniston et al., 2011). However, decision makers are increasingly recognising the need to develop better tools to manage and cope with both existing and increasing levels of uncertainty from climate variability and climate change impacts (Hallegatte, 2009). Therefore, the aim of this study is to provide key insights into how the governance of water allocation and distribution may be impacted across sectors and potential policy options for managing this under changing climate conditions. To do this, it shall provide an overview of the key vulnerability per case study, but then provide a more in depth review of the results of climate change projections on the hydrology of the upper Rhone basin in order to better contextualise and understand water governance and management challenges that the region will need to address over the next few decades.

1.1 Preparing for and responding to climate variability and change

Numerous sources and types of uncertainty exist that affect our ability to both understand and make decisions in the context of climate variability and change. Firstly, it is important to remember that water management and governance has had to develop rules or tools to manage natural climate variability, described by uncertainty ranges, (e.g. inter-annual variability of climate leading to sequences of wet and dry years). This form of ‘predictable’ uncertainty (Matthews et al., 2011) is generally indicated as stochastic variability or internal climate variability (Deser et al., 2012; Fatichi et al., 2013a).

However, climate change impacts are requiring governance frameworks and management techniques to develop approaches and adapt to more indeterminate, ‘unpredictable’ uncertainty (Matthews et al., 2011), and potentially irreversible changes in state (reduced run-off contribution from glacier and snow melt, shifts in seasonality, intensification of dry periods). The increasing diversity of future hydro-climatic conditions, or ‘non stationarity’ (Milly et al., 2008) implies that water governance cannot approach the future based on the assumption that the system will fluctuate within an unchanging envelope of variability.

Not only are the driving forces of climate highly uncertain, but fundamental scientific knowledge gaps limit the reliability of model projections (Hallegatte, 2009) with uncertainties in how climatic and non-climatic pressures will interact on different aspects of hydrology and ecology (Wilby et al., 2010). It is hoped that improved downscaling techniques can remediate some of the scale mismatches between the information provided by climate models and that required by decision makers (Hallegatte, 2009). There are also societal sources of uncertainty, not only a result of potential emission pathways, but also how populations will be able to adapt to and cope with the impacts of climate change. Traditional decision making tools and infrastructure have not been developed to take account of the broader levels of uncertainty produced by climate change projections (Hallegatte, 2009). This not only requires modellers to be careful about the communication of their results, but for decision makers and engineers to also rethink their frameworks for potential modifications to water management strategies and infrastructure, as well as moderating their expectations of direct solutions from climate science (Pielke et al., 2012).

It is increasingly recognised that both water governance and management therefore need to include climate variability in everyday operations and longer term decision making as a core component of climate change adaptation strategies (Hallegatte, 2009). An adaptable water management and governance regime therefore would not only need to manage the predictable uncertainty of climate variability (e.g. stochasticity of precipitation) but also the more unpredictable forms of uncertainty arising from climate change impacts. Water governance, the systems and rules in place that affect the use, protection, delivery and development of water resources, therefore needs to be both adaptive and flexible in developing and setting rules that regulate hydro-power, water rights allocations, urban growth and spatial planning for both current climate variability and climate change (Medema et al., 2008). Furthermore, water managers need to be able to make decisions under uncertainty, in their application of rules and the operationalisation of policy for the practical aspects of water allocation and protection, as well as protection from and during extremes (Pahl-Wostl et al., 2009).

2. Overview of Climate Change Impacts in ACQWA’s Mountain Case Areas and key vulnerabilities

This section provides a brief overview of the overview of the key climate change impacts in each case area as well as the implications for key water use sectors.

2.1 Upper Rhone Basin, Switzerland

- Summer & spring drying; wetter winters; temperature increases by 2050 (0.85-0.93°C).
- Earlier snow-melt (5-10 days); increased melt in April and May
- Significant reduction in glacier melt contribution expected by 2050 (70%); constriction of the period significant melt; decrease in summer run-off (25%: Rhone; 50%: high elevation glaciered catchments).
- Decreased frequency of debris flows, but increase of the magnitude of events due to higher precipitation intensities and larger sediment sources.
- Seasonal output is likely to be more modified with decreasing flows in low-demand periods (Jul/Aug) and increasing flows in high demand periods (Apr/May). Total annual decrease in ice fed reservoirs is likely to negatively affect production.
- Increase in consumption due to crop evapotranspiration (+10% in July at Visp), potential water shortages for crop growth would be more likely. More pressure placed on small rivers with fewer water supplies from glaciers. Less impact at catchment scale, but local critical situations during the late summer might occur.

2.2 Po Basin, Italy

- From 2001-2010 to 2041-2050Increase of temperature ranges between 15.2% and 17.5%, and variation of mean annual precipitation ranges from 1.1& to 9.6% (mainly Jan-Mar).
- Accelerated melting periods; increase in evapotranspiration (summer) counteracts the influence of the larger amounts of summer precipitation on river discharge.
- Decrease of flow discharge is estimated to be more than 50% of the seasonal average for a large portion of the drainage network.
- Shifts in seasonality will affect the rules governing dam management to take into account increased availability of water in the earlier months of the year and a longer summer period with much less water left for the runoff.
- Despite the farmers' observed investments to adapt to mean changes in climate at local level, unanticipated variability in climate continues to impact crop yields.

2.3 Syr Darya Basin, Kyrghistan

- Decrease in summer precipitation (4-7%); increase in winter precipitation (4 to 8%) by 2050. Temperature increases are projected (+2.6-4.4°C) for all seasons.
- More extreme events: summers droughts and winter/spring floods.
- Loss of glacier volume (0.9% p/y) eventually leading to decrease of glacier-fed summer runoff.
- Earlier and more intense snowmelt; decrease in snow cover duration.
- More importance placed on the buffering effect of glaciers to release additional water during dry summers in compensation for rain shortfalls for domestic, industrial and irrigation requirements. However, a tipping point is likely to be reached when glacier contributions diminish.

- Irrigation demand (cotton, wheat) accounts for 90% of water demand in the region, is vulnerable to drought and increased variability from climate change impacts.
- Total hydropower potential of the rivers may decrease by 14%.

2.4 Aconcagua Basin, Chile

- Warmer winters; Decreasing precipitation, changes in snowpack, changes in the timing of snow and glacier melt and generally increasing dry period.
- Shifts in seasonality and decreases in glacier melt are particularly significant in the Andean region due to the high dependence on glacier and snow melt run off for water availability during the dry summer months.
- Decreasing amounts of precipitation during summer are likely to be exacerbated by a decrease of glacial melt-water releases in the long-term due to reduced glacier volume impacting summer irrigation of water intensive crops (e.g. avocado, table grapes).
- Water transfers across the basin for water resources supply have already been undertaken.
- Reduced run-off in summer is likely to affect the management of run of the river hydropower plants.

3. Focus on physical climate change impacts in the upper Rhone basin

In order to provide a more in depth analysis as to how the governance of water allocation and distribution may be impacted across sectors and potential policy options for managing this under changing climate conditions, this study focusses on conducting an in depth analysis of the upper Rhone basin, the key case study in the Swiss Alps. The following sections therefore present an overview of the key climate change impacts on the hydrological regime of the upper Rhone basin, resulting from the scientific deliverables of ACQWA. A full presentation of the different methodologies, models and detailed analysis can be found in the individual papers (Fatichi et al., 2013b; Fuhrer et al., subm; Gobiet et al., subm.; Stoffel et al., subm) from which these highlights are taken.

3.1 Precipitation and temperature

While it is difficult to draw conclusions for changes in total precipitation and seasonality due to low signal-to-noise ratio, a more pronounced summer drying was identified at low elevations, as were slight increases of wintertime precipitation that are largest in the lowlands (Gobiet et al., 2014.). Stochastic downscaling of different climate models suggest that by 2040-50 average precipitation in the entire upper Rhone basin could change by -5% to +10% (-70 to +120 mm yr^{-1}) in comparison to the present day climate, as well as a slight significant tendency of increasing precipitation in the period February to April and September to October (Fatichi et al., 2013b). Uniform temperature increases of about 0.6-0.7°C for the period 2030-2040 and up to 0.85-0.93°C for the period 2040-2050 are simulated with a slightly larger increase in summer than winter (Gobiet et al., 2014; Coppola et al., 2014). While stochastic variability of air temperature is far below the expected changes, it should be added that uncertainty in projecting change in air temperature is mostly related to the choice of the climate model (all of the ACQWA scenario use the same driving GCM). A detailed investigation of the characteristics of daily precipitation and temperature extremes during the period 2031-2050 (for each season) reveals that no significant trend is detected for the signal of extreme precipitation events in comparison to the control period. However, an intensification of temperature is projected to be significant (Im et al., 2010).

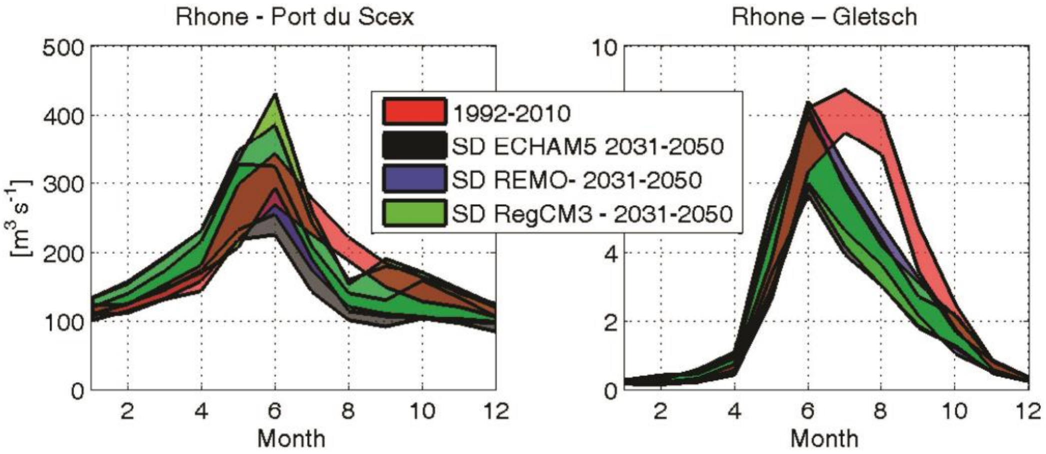
3.2 Snow and ice

Glacier melt at the catchment scale is simulated to progressively decrease by about 100 mm yr^{-1} (roughly 70% less than the current value) by the 2040-2050 period, since the peak of glacier melt is likely to have already been surpassed. However, uncertainties related to initial conditions (glacier thickness at the beginning of the simulations) might shift this projection by 10-20 years. Seasonality of glacier melt is expected to change, significantly reducing the major glacier melt contribution during June to October to a lower contribution during the period July to September (e.g., Paul, 2011). Catchments with mainly low-elevation glaciers are the most affected by the reduction. Total snow melt is consistently projected to either remain the same or increase due to increasing precipitation from February to April. The major signal of change is an increase in snow melt at very high elevations (>3000m) in the months of April and May due to the earlier start of snow melting (5-10 days) and most importantly to the greater levels of snow deposited, induced by higher winter precipitation (Beniston, 2012).

3.3 Runoff

Average runoff in 2040-50 is predicted to remain the same or to slightly decrease (<5% - 10%) from current conditions, related mainly to a significant reduction in ice-melt. However, since the change signal of runoff over a 10-year period is comparable or smaller than the stochastic variability of precipitation, any assessment about future change is highly uncertain. The overall climate change effect on runoff is strongly elevation- and glacier-dependent, being more significant and less uncertain in high elevation catchments fed by glaciers, but dampened downstream at lower elevations (Finger et al., 2012; Fatichi et al., 2013b). An increase in runoff during April and May is more consistently expected (especially in western parts) due to the earlier snow melt and increased winter precipitation (Figure 1). For the period 2040-50, summer runoff (July to September) is expected to become significantly smaller for the entire Rhone (25% reduction) and especially for high elevation glaciered catchments (50% reduction). For basins without upstream glaciers, the decrease is not significant.

Figure 1: Using two exemplary stations (the outlet and the most upstream and glaciarised) to illustrate change in seasonality. The reduction of streamflow due to glacier melt in Gletsch is contrasted by the less important effect at the entire catchment scale (Source: Authors' own).



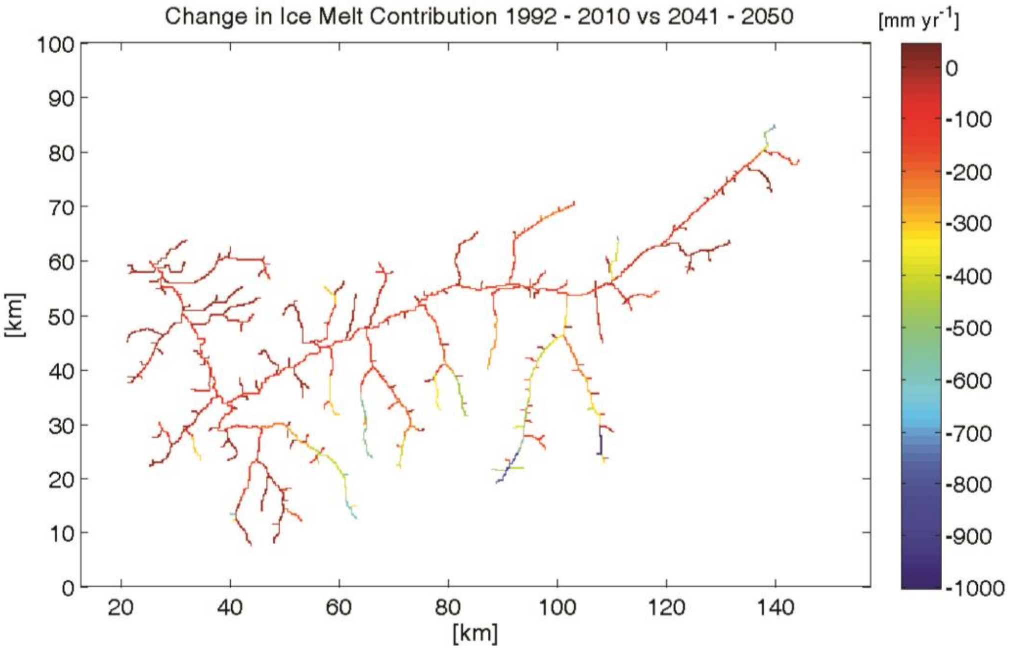
3.4 Floods and hazards

Despite the inter-annual variability of precipitation, an increase of maximum hourly (+25%) and maximum daily discharge (+10-20%) is projected across the entire catchment, suggesting no major change in flood occurrence. The frequency of debris flows is likely to decrease in many basins as a result of fewer precipitation events in summer, but the magnitude and devastating potential of events might increase due to higher precipitation intensities and larger sediment sources (Stoffel et al., 2011). In addition, as a consequence of climate warming, the period during which debris flows occur is likely to increase as well, so that events may become possible between May and late October in the future (Stoffel et al., in press). Rockfalls from altitudes controlled by permafrost (mostly above 2500 m a.s.l) are expected to become more frequent (Stoffel and Huggel, 2012), leading to possible risks for infrastructure and transportation corridors at higher elevations.

3.5 Sector specific impacts: hydropower and agriculture

Hydropower production contributes to 55% of Swiss electricity consumption, a third of which is generated in the Valais (SFOE, 2012). The impact of climate change on market supply therefore has the potential to be significant. Run-of-river, pump-storage and storage-hydropower, all found in Canton Valais, will be affected in different ways by climate change, with pump storage being the least affected (Gaudard et al., 2014). Run-of-river installations (one third of cantonal production), providing base-load energy with seasonal fluctuations, are mostly situated on the plain. While climate change is unlikely to affect annual output of downstream rivers, seasonal output is likely to be modified quite strongly, with decreasing inflows during the summer period (lower consumption periods) and increasing inflows between May and April (higher consumption periods). Storage-hydropower plants are a more flexible technology with modifiable production periods, whose revenues are less vulnerable to shifts in seasonality than run-of-river. While more even contribution from runoff might advantage reservoir management, a decrease in total annual runoff expected for reservoirs fed by ice melt is likely to negatively affect production (Figure 2).

Figure 2: Stochastic downscaling showing that reservoirs fed by glaciers are likely to be more impacted than those that are not ice fed (Source: Authors' own).



With increasing temperatures, it can be expected that water consumption through crop evapotranspiration would increase (e.g. average +10% in July at Visp across a range of climate scenarios up to 2049) (Smith et al., subm). In drier areas with low summer precipitation (much of the valley floor and the south-facing slopes), potential water shortages for crop growth would be more likely, necessitating additional irrigation to maintain optimal crop yields (max. +35%). During extremely dry years, irrigation requirement increases would be much higher, potentially exceeding surface water availability in smaller catchments with a nival runoff regime (e.g. Sionne) where water is drawn through small irrigation channels for grassland irrigation (Fuhrer et al., 2014). High demand for water for irrigation will likely put additional pressure on small rivers in catchments with little or no water supply from glaciers (Smith et al., 2012), while the larger water sources at the valley bottom may not be subject to the same extent of variability (Fuhrer and Jasper, 2012).

4. Key challenges across sectoral policy and governance contexts

These modifications in quantity and timing have potentially significant ramifications for water governance and management. In particular, the high spatial and temporal resolution of the models used in ACQWA underline the complexities of expected changes at the catchment and temporal scale, while reinforcing the general trend of impacts for the basin as a whole. According to the projected impacts detailed in Section 2, water managers will broadly need to prepare for a number of general trends at the basin level, including potential increases in runoff in late winter and autumn (mainly in the west) and potential decreases in spring and late summer (less likely in the west). Snow melt is likely to take place earlier, with increased melt in April and May, but less change will be noticed at lower than higher elevations. One of the strongest effects is the significant reduction in glacier melt contribution expected by the middle of the century, and a constriction of the period where glacier melt is significant (shifting from June to October to July to September) that will have serious repercussions for the management of hydropower reservoirs, dependent on elevation and the extent of glaciers in each catchment. However, results show that while modifications to seasonal output are likely, they are tempered by the fact that decreasing flows in low-demand periods (Jul/Aug) and increasing flows are expected in high demand periods (Apr/May). However, although in the short run increasing flows may favour higher production in ice-fed reservoirs, the longer term total annual decrease in ice-fed reservoirs is likely to negatively affect production.

While at the catchment scale irrigation is unlikely to be significantly affected by climate change, local critical situations during the late summer might begin to occur during the coming decades due to the increase in consumption because of higher crop evapotranspiration. In order to better understand the framework within which water managers will need to adapt to spatially and temporally diverse impacts, this section reviews the policy and legislative context according to a set of criteria related to interactions across sectoral policy frameworks, spatial and temporal scales in order to understand how climate change might impact the system.

4.1 Tensions across sectoral policy frameworks

Areas of interaction between sectoral and environmental policy can lead to synergies or conflicts, such as that between renewable energy and water protection (Nilsson et al., 2012). The challenge of balancing diverse interests in water resources is well known from the integrated water resources management literature (Engle et al., 2011). In social ecological systems, existing tensions (e.g. across sector, scale, actor groups, rates of change) can be further heightened by changes in the physical system (Hill and Engle, 2013). Expert interviews, grey literature and desktop review of the policy and legislative framework at national and local scales have highlighted tensions between earlier exploitation rights, more recent protection laws, as well as energy and integrated water resources management (IWRM) federal policy priorities (Beniston et al., 2011; Hill, 2010; Hill, 2013; Hill and Engle, 2013).

Despite federal policy initiatives for IWRM, there is no framework for basin management or IWRM for the Rhone basin, undermining horizontal and vertical institutional coordination (Hill, 2010). In part this has led to tensions relating to agricultural development and land use (including zoning and spatial planning), and the quantitative protection of water resources and aquatic ecosystems. The dual push for renewable sources (Federal CO2 Law, 2011; Federal Energy Act (art.3); BFE, 2009; FOE, 2008) and new policy objectives to phase out nuclear power (FOE, 2013) signals an increasing reliance on hydropower. Concurrently, a number of developments have occurred in the qualitative (Water Protection Act, art.3, 6 ,80) and quantitative (WPA, art.30, 32) protection for waterways and native aquatic fauna (Federal Forest Act, art. 7 – 10). In Valais, the level of protection of aquatic ecosystems (Valais Law on Hydraulic Engineering, art.5 & art. 39) is diluted by cantonal emergency powers (art.32), specific requirements on elevations above 1000m, the vagueness of the criteria to be applied and the need to consult with interested parties when fixing residual flows (art.35).

On the other hand, the Cantonal Law on Utilisation of Hydropower provides for the prioritisation of irrigation rights over residual flows and hydropower concessions from April to September (art.42). Alpine farming and traditional infrastructure are also afforded protection through the Valais Law on Agriculture (art.59). In the case of flood management, federal principles on sustainable flood protection (e.g. natural retention zones, identification of ecological deficits) (SAEFL, 2003) are supported by procedural rules in the Cantonal Law (and Ordinance, art. 14) on the Management of Watercourses to ensure that minimum requirements (enlargements and slow flowing zones) for meeting security and ecological objectives are fulfilled. Despite the aims of integration (Valais, 2009b), related projects such as the Third Rhone Correction (TRC) have been controversial in implementation, particularly in terms of the Canton Valais' acquisition of 100 hectares, mainly from agricultural land.

There are therefore three distinctly separate and segregated foci across different laws and policies: those that provide for the protection of natural flows and state of watercourses, diversity and habitats, including enhanced ecological room and functioning for more sustainable flood management; those prioritising specific agricultural uses and agricultural development; and those prioritising renewable energy production, which is likely to be water intensive. The current lack of integrative catchment management at the canton level means that while certain policies might be becoming integrative (e.g. flood management), it remains divisive in implementation and does not account for priorities set in other sector laws or policies.

4.2 Challenges across spatial and temporal scales

Climate policy is a key area in which the challenges of short and long term adaptation across governance scales can be addressed (Brouwer et al., 2012). In 2012, the Federal Council launched their adaptation strategy, detailing the principles that will define adopted measures, and explicitly acknowledging the interfaces between the different sectors relevant to adaptation (FOEN, 2012). Although so far limited to the federal level with as yet no concrete measures proposed (FOEN, 2012), adaptation options are recognised as having potential implications for the cantons or communes once pilot programmes have been launched (FOEN, 2013), as well as requiring increased institutional coordination. In the Valais, the TRC is one of the few examples of the specific inclusion of climate change uncertainties and risks in water resource policy through the concept of 'residual risk' in the modification of flows, thereby addressing both short and long time scales (Valais, 2009b). The longer time horizons set in the TRC management plan signal a shift to more iterative, integrative and variable risk-based strategies, acknowledging that current flows may be surpassed in the future. The nascent MINERVE system (a public – private partnership between Canton Valais, a federal university, Météosuisse, and hydropower companies to improve the modelling of and response network for extreme events) also aims to provide extra retention through the hydropower reservoirs, with special evacuation corridors being utilised in major precipitation events.

The impacts on glacier fed reservoirs will need to be managed within the context of hydropower concessions that are often fixed for a maximum duration of 80 years. The long term rights of use are therefore less flexible than more local regulations that govern pricing, potentially undermining environmental provisions and emergency planning. For example, in times of scarcity, local utilities may request hydropower companies to replenish regional reservoirs, but no fixed emergency plan for periods of scarcity is likely to be implemented before the next round of concession renegotiations, which in some cases will not take place until 2040 (Hill, 2013). Across spatial scales, the lack of cantonal oversight over planning and water related developments at the commune level (e.g. challenges in developing a cantonal energy plan) make coordinated responses to climate change difficult (Hill and Engle, 2013). Similarly, at the canton level stakeholders spoke of the drive to create a more uniform approach to natural hazards in their monitoring and management for a more integrated strategy and longer term protection (Hill and Engle, 2013). An integrated catchment approach to hydrological analysis, as presented by Fatichi et al. (2013b), might represent a blueprint for such future analysis. Positively, technical support is provided from federal and cantonal authorities, for commune level tasks such as emergency and hazard planning.

5. Policy Alternatives: Adapting to a changing context

Water governance and management will need to be simultaneously prepared for both short-term and long-term issues relating to natural climate variability and shifts imposed by climate change. Despite the general acceptance on the need to better integrate stochastic climate variability (Milly et al., 2008), opinion is still divided on how to integrate uncertain climate change impacts (Wilby et al., 2010). Many scientists suggest that the answer lies in increasing investment in climate model resolution and data (Hawkins and Sutton, 2009). However, results in section 2 support suggestions that a high level of uncertainty is likely to continue to challenge longer term decisions on adaptation to climate change impacts (Dessai and Hulme, 2007). However, significant economic costs are likely to be incurred if decisions are only made once there is certainty about how climate change impacts will manifest (Hallegatte, 2009).

5.1 Principles for policy options

The growing body of literature on institutional and governance indicators of adaptive capacity in social-ecological systems (Engle and Lemos, 2010; Nelson et al., 2007) suggests that iterative, collaborative (connective), and flexible approaches can increase adaptive capacity and support the sustainability of water systems (Huitema et al., 2009;

Pahl-Wostl et al., 2007). Actionable measures, however, still remain elusive (Wilby et al., 2010). After presenting the different principles proposed to guide policy developments for adaptation in water resources management and governance, actionable measures are proposed that may help alleviate underlying tensions (section 3) likely to be exacerbated by climate change impacts (section 2).

5.1.1 Iterativity: allowances for reassessment; periods of review; mainstreaming climate data in monitoring & observation; ability to inform decision making for course changing when necessary.

Provisions that allow for structured processes of review (e.g. every 10 years in the TRC) should be considered not only in areas of flood management and spatial planning, but equally in areas of contract and administrative law that govern hydropower concessions and irrigation prioritisation. The structured modalities of evaluation and revision in the action plan of the Federal Adaptation Strategy (FOEN, 2012) are a promising start, and should be replicated in any regional or cantonal level adaptation plans. Furthermore, long term planning horizons (e.g. 20 year planning process updated every 5 years) should be institutionalised for canton and commune level infrastructure and development plans in order to better anticipate future problems (Hallegatte, 2009).

From a management perspective, ensuring that the structures are in place to include new and emerging climate data into management decisions (e.g. for supply or flood management) is a good starting point. This not only means ensuring that climate data is included in the monitoring, observation and simulation data, but that this data is consistent, accessible, and affordable for incorporation into decision making. Furthermore, enhancing the redundancy in the supply system to buffer potential increases and decreases, will allow the requisite scope to integrate new data or information as and when it is available.

5.1.2 Flexibility: redundancy; flexible resource management; learning; agency and autonomy at the appropriate scales; ability to change course when necessary.

Local actors require flexibility to react and plan according to their individual needs. In the Valais, the rules and regulations which guide water pricing, provision and use tend to be set in commune or canton level regulations and contracts, which allow for some flexibility in revising rules to adapt to new challenges (Hill, 2013). Legal safeguards could be creatively restructured by law makers to allow public authorities more flexibility to deal with climate change impacts, such as increased emergency authority, post-decision evaluation and the use of administrative procedures for specific implementation decisions (Craig, 2009).

Safety margin strategies for calibrating supply or drainage infrastructure are recommended in order to '*transform the uncertain annual loss… into a certain and manageable loss'* (Hallegatte, 2009, p245). For example water managers in Copenhagen use run-off figures that are 70% larger than their current level (Hallegatte, 2009). In Valais, lessons could be learnt from MINERVE and the TRC for introducing redundancy into the system to cope with uncertain climate impacts (e.g. enhanced storage capacity, evacuation corridors, enhanced flood plain functioning). From a supply perspective, increased storage capacity and artificial springs might be technical options for buffering a more extreme climate (FOEN, 2012).

5.1.3 Connectivity: networks and connections between processes and scales; matching and adapting agency and authority; autonomy at lowest suitable level (subsidiarity); integration and coherence across adaptation-mitigation-resource policy.

Decisions affecting land, agriculture, ecosystem well-being, and flood protection affect multiple sectors and scales. While participative processes can improve the integration of different issues in decision making, the added complexity must be aptly managed (Hill and Engle, 2013). Financial incentives, such as subsidies, can be a key tool for public authorities to address intra-jurisdictional challenges and to craft responses that build social-ecological resilience. Many existing partnerships in Valais tend to be sector specific, but effectively enable the sharing of best practices, technologies, and learning across communes and cantons. Formalising collaborative interactions across some of these existing networks could improve cross-sector engagement on climate challenges, and balance intersections across different development and planning areas.

Climate change impacts potentially expose government to increased financial liability as local and regional governments are less able to finance responses to extreme events (FOEN, 2011), thereby necessitating innovating in financing reactive and proactive adaptation across different scales of government (e.g. innovations in insurance). Furthermore, climate policy needs to account for interconnections and interfaces between mitigation, adaptation and other sectoral priorities in order to address multi-sectoral trade-offs (e.g. enhancing wetlands for flood management, biodiversity, and carbon sequestration, ensuring adaptation options do not lead to increased energy use). From a management perspective, enhancing the regional connectivity of the supply and wastewater system has been highlighted in the federal adaptation strategy (FOEN, 2012) and is particularly relevant in Valais. Likewise, augmenting the integration and comprehensiveness of reservoir and lake management for multiple adaptation purposes (e.g. flood prevention, irrigation water, water for energy) will be particularly important in the Alpine context.

5.2 Proposing actionable measures

In light of these continuing challenges concerning uncertainty, studies recommend strategies that are no-regret, reversible, flexible and iterative, that take a long term and soft approach (rather than purely hard infrastructure based) and integrate both adaptation and mitigation requirements (Clarke, 2009; Hallegatte, 2009; Hill, 2013; Wilby et al., 2010). Furthermore, it should be added that the climate models used within the ACQWA simulations are relatively soft within the family of models associated with the SRES A1B scenario (which itself is a medium range emissions scenario) (Beniston et al., 2014; Gobiet at al., 2014) (IPCC, 2000), which further underlines the need for responses that are appropriate to an even more extreme hydro-climatic changes that those presented in Section 2 and Table 1 below. Infrastructure will likewise need to be robust to flows of a larger range than prior climate conditions, but which in itself will be highly uncertain. In this regard, the importance of accounting for natural climate variability and change through stochastic approaches that examines multiple possible trajectories is stressed (Fatichi et al., 2013a, b).

Table 1 draws on the principles detailed in the previous section in order to present a set of corresponding specific actionable measures that could assist policy makers in navigating the tensions and challenges elucidated in the previous sections. These principles should help guide policy makers to better prepare the systems for which they are responsible to cope with uncertainties from climate variability and climate change (Figure 3).

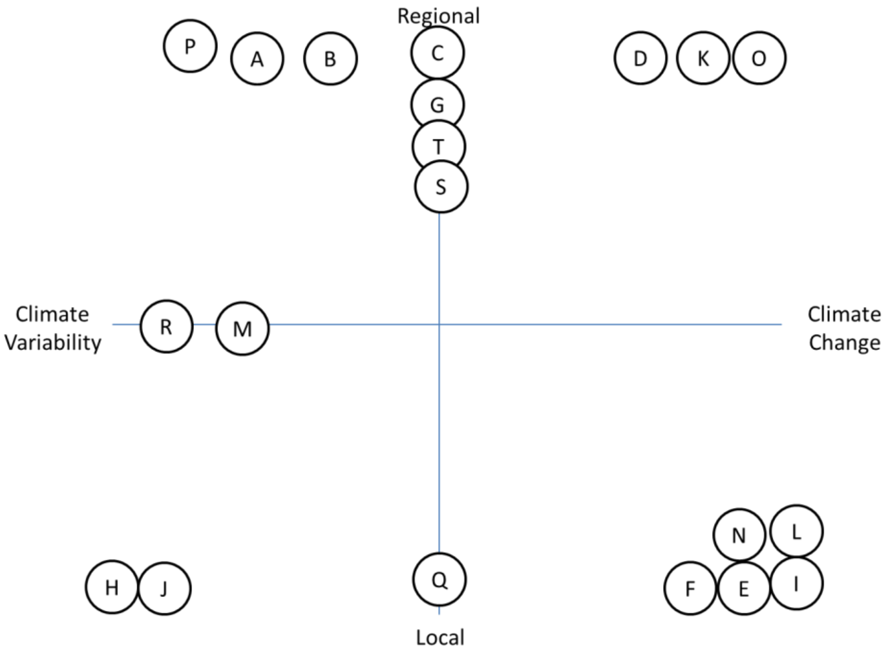
Table 1: Integrated analysis of climate and governance challenges with proposed actionable measures.

Climate Pressure	Current Challenges	Actionable Measures
Precipitation Potential increase: Feb/Mar/Apr & Sept/Oct in West/South-West Potential decrease: May & Jul/Aug in East, North & South tributaries, main valley. More likely larger discharges in Western upper Rhone	- Small scale arrangement of water supply. High levels of autonomy at municipal level block longer term catchment scale planning and smoothing of bottleneck periods. - Sectoral focus. - Lack of integrative adaptation planning at canton level. - Flood policy is integrative, but divisive in implementation. - Spatial planning led to a decrease in resilience due to concreting of river reaches.	A) Formalisation of current regional networks. B) Improve inter-linkages of local supply network of water and wastewater utilities. C) Monitoring and observation (extend application of data; integration of climate projections). D) Integrated assessment of development & adaptation: evaluate possible conflicts and synergies (e.g., agricultural development, habitat conservation, energy security and ecosystem service provision). E) Update of hazard plans to include emerging hazards. F) Preparation of civil protection forces for increased flooding, forest fires, amongst others. G) Development or formalisation (provide legal basis) of disaster funds, financial assessments, and financing of ecosystem based and technical hazard prevention. H) Hazard mapping and zone planning, integrated with agricultural development or management (e.g. art. 3, Spatial Planning Act). I) Develop multi-purpose use of reservoirs and lake regulation. J) Restoration of riparian habitats: recreation of riparian buffer zones, wetlands and active floodplains (potential demonstration sites).
Glacier Melt Reduction in period with significant glacier melt. Significant reduction in glacier	- Fixed and long term of concessions that do not account for impacts on hydropower production and	K) Establish periods of review for provisions concerning existing concession provisions or calculation bases for residual flows as discharge patterns are modified. L) Adaptation of reservoir management & hydroelectric power generation to changing flow rates and regimes as snow and ice patterns change.

melt contribution by 2050 (70%). **Snow-Melt / Snow-Line** Increase Apr/May Earlier snow melt (5-10 days) Less change at lower elevations	timings. - Lack of formal rules on certain uses. New, un-regulated uses (e.g. increasing use of snow-making). -Local critical situations in specific catchments.	M) Formalisation of regional networks for water management: establish common principles for management of water bodies and resources across energy, tourism, domestic and ecological requirements. N) Diversify tourism adaptation so it is less dependent on snow-making post 2050. O) Regional adaptation planning that takes into account conflicts and synergies between strategies.
Runoff Potential decrease (Jul/Aug/Sep) - 25% in Rhone River; 50% in high elevation glaciered catchments. Potential increase (Apr/May) Elevation & Glacier dependant	- Bottleneck periods for local water supply. - Lack of demand management integrated into spatial planning. -High levels of autonomy at municipal level block longer term catchment scale planning and smoothing of bottleneck periods. - Lack of formal mechanisms to manage competition across catchment areas.	*K*); P) Establish rules and procedures at cantonal level (ref Walter Postulate for Federal Level) for water distribution during bottleneck periods/periods of water shortage; Q) e.g. enhanced demand management to reduce both surface and groundwater abstractions; time limited licensing, local and periodic restrictions, compensation schemes, water recycling. R) Promote best agricultural practice for land and water management (reduce water requirements by increasing the water retention and storage capacities of soils, selecting suitable plant breeds and optimising irrigation systems). *M*);S) Re-orientation of water management at regional rather than local level; diversification and optimisation of water reserves, reservoirs and lakes. T) Bring land and water managers together for integrated catchment area management.

Balancing interests across spatial and temporal scales can lead to challenging trade-offs, notably when short-term adaptations at one governance scale, may potentially undermine long-term social-ecological resilience at another governance scale (Adger et al., 2011; Hill and Engle, 2013). Figure 4 elucidates how the actions listed in Table 1, cover the different requirements of water managers and policy makers to meet these dual challenges of uncertainty and scale. Presenting the measures in such a format, could help to guide the application of scarce finances and resources to ensure that both sets of challenges are addressed, and that adaptation is not potentially hindered by existing and underlying governance and management challenges.

Figure 3: Responding to different forms of uncertainty and challenges of scale (adapted from Hill & Engle, 2013; Muir et al, 2012 to correspond to the actionable measures proposed in table above). The letters correspond to the actionable measures proposed in Table 1 above.



6. Conclusions

In this deliverable we have sought to scope the key vulnerability and challenges across different sectors. By presenting an in depth analysis as to how the governance of water allocation and distribution may be impacted across sectors in the upper Rhone basin, we have sought to draw out potential policy options for managing both changing climate impacts and underlying uncertainty. More specifically, we have focussed on the upper Rhone basin in Switzerland to analyse in depth both climatic and governance pressures on water resources, in order to better understand the current limitations in water management approaches to dealing with climate change impacts. Evidence from the hydrological modelling outputs from the ACQWA project suggest that climate change impacts are likely to alter the timing of snow and mostly volume of glacier melt, and thus have implications for local water provision, hydropower production and irrigation requirements in certain catchments. Governance analysis from ACQWA shows that challenges already persist in the governance and management of water, in particular those relating to the sectoral and small scale arrangement of water governance, lack of rules on emerging challenges and uses, and the inflexible and long term nature governing certain uses as hydropower exploitations.

Climate change impacts are likely to exacerbate these issues, by introducing an extra layer of uncertainty and shifting the hydrological baselines upon which fixed and un-integrated rules and policies are based on at different governance scales and across different sectors. The significant enhancement in the spatial and temporal resolution of the climate change impact projects for the upper Rhone basin, the ACQWA results underline the complexities of expected changes at the catchment and temporal scale, while also reinforcing the overall basin response, delineating the local and regional challenges and tensions that must be managed, despite the remaining uncertainties. Finally, the paper presents a set of principles (flexibility, iterativity and connectivity) that have emerged to assist water managers and policy makers in navigating these challenges of uncertainty and scale. Since it is vital to move beyond general principles to more actionable measures, we presented a set of actionable measures that address challenges across both temporal and spatial scales. Future work should monitor the implementation of such measures to ensure that new information is integrated, trade-offs are limited, and any negative feedbacks halted.

References

Adger, W.N., Brown, K., Nelson, D.R., Berkes, F., Eakin, H., Folke, C., Galvin, K., Gunderson, L., Goulden, M., O'Brien, K., Ruitenbeek, J., Tompkins, E.L. (2011) Resilience implications of policy responses to climate change. WIREs Climate Change 2, 757-766.

Beniston, M. (2004) Climatic change and its impacts. An overview focusing on Switzerland. Kluwer Academic Publishers, Dordrecht/The Netherlands and Boston/USA.

Beniston, M.**,** 2012. Is snow in the Alps receding or disappearing? WIRES Climate Change 3, 349–358.

Beniston, M., Stoffel, M., Hill, M. (2011) Impacts of climatic change on water and natural hazards in the Alps: can current water governance cope with future challenges? Examples from the European "ACQWA" project. Environmental Science and Policy 14 734-743.

Beniston, M., Stoffel, M., 2014: Assessing the impacts of climatic change on mountain water resources. Science of the Total Environment, in press.

BFE, (2009) Kostendeckende Einspeisevergütung (KEV). Bundesamt für Energie. Available at: http://www.bfe.admin.ch/themen/00612/02073/index.html (accessed 9 June 2009).

Brouwer, S., Rayner, T., Huitema, D. (2012) Mainstreaming climate policy. The case of climate adaptation and the implementation of EU water policy. Enviroment and Planning C. Accepted.

Clarke, S.J. (2009) Adapting to climate change: implications for freshwater biodiversity and management in the UK. Freshwater Reviews 2, 51-64.

Coppola, E., Verdecchia, M., Giorgi, F., Colaiuda, V., Tomassetti, B., Lombardi, A., 2014. Changing hydrological conditions in the Po basin under global warming. Science of the Total Environment, in press.

Craig, R.K., (2009) 'Stationariy is dead' - Long Live Transformation: Five Principles for Climate Change Adaptation Law. Florida State University, U.S.A.

Deser, C., Phillips, A., Bourdette, V., Teng, H. (2012) Uncertainty in climate change projections: the role of internal variability. Climate Dynamics 38, 527–546.

Dessai, S., Hulme, M. (2007) Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. Global Environmental Change 17, 59-72.

Engle, N.L., Johns, O.R., Lemos, M.C., Nelson, D.R. (2011) Integrated and adaptive management of water resources: Tensions, legacies, and the next best thing. Ecology and Society 16 19. [online] URL: http://www.ecologyandsociety.org/vol16/iss11/art19/.

Engle, N.L., Lemos, M.C. (2010) Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil. Global Environmental Change 20, 4-13.

Fatichi, S., Ivanov, V.Y., Caporali, E. (2013a) Assessment of a stochastic downscaling methodology in generating an ensemble of hourly future climate time series. Climate Dynamics 40, 1841-1861.

Fatichi, S., Rimkus, S., Burlando, P., Bordoy, R., Molnar, P. (2013b) Elevational dependence of climate change impacts on water resources in an Alpine catchment. Hydrology and Earth System Science Discussion 10, .

Finger D, Heinrich G, Gobiet A, Bauder A, 2012. Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century, Water Resources Research 48, W03903.

FOE, (2008) Actionplan 2008 for Energy Efficiency and Renewable Energy. Federal Office for Energy, Bern, Switzerland. Available at: http://www.bfe.admin.ch/themen/00526/02577/index.html?lang=de.

FOE, (2013) Energy Strategy 2050. Federal Office for Energy, Bern, Switzerland. Available at: http://www.bfe.admin.ch/themen/00526/00527/index.html?lang=de.

FOEN, (2011) Leben mit Naturgefahren: Ziele und Handlungsschwerpunkte des Bundesamts für Umwelt (BAFU) im Umgang mit Naturgefahren. Federal Office for the Environment: Natural Hazards Prevention Division, Bern, Switzerland.

FOEN, (2012) Adaptation to climate change in Switzerland - Goals, challenges and fields of action. Federal Office for the Environment, Bern, Switzerland.

FOEN, (2013) Lancement du programme pilote «Adaptation aux changements climatiques». Federal Office of the Environment. 18.03.2013 [online] Available at: http://www.news.admin.ch/message/index.html?lang=fr&msg-id=48192.

Fuhrer, J., Jasper, K. (2012) Demand and supply of water for agriculture: influence of topography and climate in pre-alpine, mesoscale catchments. Natural Resources 3, 145-155.

Fuhrer J, Smith P, Gobiet A, 2014. Implications of climate change scenarios for agriculture in alpine regions – A case study in the Swiss Rhone catchment. The Science of the Total Environment, doi:10.1016/j.scitotenv.2013.06.038

Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, Stoffel M, 2014. 21st century climate change in the European Alps – A review. Science of the Total Environment, doi: 10.1016/j.scitotenv.2013.07.0.

Hallegatte, S. (2009) Strategies to adapt to an uncertain climate change. Global Environmental Change 19, 240-247.

Hawkins, E., Sutton, R. (2009) The Potential to Narrow Uncertainty in Regional Climate Predictions. Bulletin of the American Meteorological Society 90, 1095–1107.

Hill, M. (2010) Converging Threats: Assessing socio-economic and climate impacts on water governance. International Journal of Climate Change Management and Strategies 2, 242-263.

Hill, M. (2013) Climate Change and Water Governance: Adaptive Capacity in Chile and Switzerland. Springer, Heidelberg, Germany.

Hill, M., Engle, N.L. (2013) Adaptive Capacity: Tensions across Scales. Environmental Policy and Governance 23, 177–192.

Huitema, D., Mostert, E., Egas, W., Moellenkamp, S., Pahl- Egas, W., Moellenkamp, S., Pahl-Wostl, C., Yalcin, R. (2009) Adaptive water governance: Assessing the institutional prescriptions of adaptive (co-)management from a governance perspective and defining a research agenda. Ecology and Society 14, 26. [online] URL: http://www.ecologyandsociety.org/vol14/iss21/art26/.

Im, E., Coppola, E., Giorgi, F., Bi, X., 2010. Validation of a high-resolution regional climate model for the alpine region and effects of a subgrid-scale topography and land use representation. Journal of Climate 23, 1854–1873.

IPCC, (2000) IPCC Special Report on Emissions Scenarios: Summary for Policymakers. A Special Report of IPCC Working Group III. Intergovernmental Panel on Climate Change, Available online: https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf.

Matthews, J.H., Wickel, B.A.J., Freeman, S. (2011) Converging Currents in Climate-Relevant Conservation: Water, Infrastructure, and Institutions. PLoS Biology 9, e1001159.

Medema, W., McIntosh, B.S., Jeffrey, P.J. (2008) From Premise to Practice: a Critical Assessment of Integrated Water Resources Management Ecology and Society 13, 29. [online] URL: http://www.ecologyandsociety.org/vol13/iss22/art29/.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J. (2008) Stationarity Is Dead: Whither Water Management? Science 319, 573-574.

Nelson, D.R., Adger, W.N., Brown, K. (2007) Adaptation to environmental change: Contributions of a resilience framework. Annual Review of Environment and Resources 32, 395-419.

Nilsson, M., Zamparutti, T., Peterson, J.E., Nykvist, B., Rudberg, P., McGuinn, J. (2012) Understanding Policy Coherence: Analytical Framework and Examples of Sector-Environment Policy Interactions in the EU. Environmental Policy and Governance Wiley Online Library.

Ostrom, E. (2007) A diagnostic approach for going beyond panaceas Proceedings of the National Academy of Sciences of the United States of America 104, 419-422.

Pahl-Wostl, C., Kabat, P., Möltgen, J., (2007) Adaptive and Integrated Water Management. Coping with Complexity and Uncertainty. Springer Verlag, Berlin, p. 440.

Pahl-Wostl, C., Sendzimir, J., Jeffrey, P. (2009) Resources Management in Transition. Ecology and Society 14, 46. [online] URL: http://www.ecologyandsociety.org/vol14/iss41/art46/.

Paul, F., 2011: Melting glaciers and icecaps. Nature Geoscience, 4 (2), 71-72

Pielke, R.A.S., Wilby, R., Niyogi, D., Hossain, F., Dairuku, K., Adegoke, J., Kallos, G., Seastedt, T., Suding, K., (2012) Dealing with complexity and extreme events using a bottom-up, resource-based vulnerability perspective, in: Sharma, A.S. (Ed.), Extreme Events and Natural Hazards: The Complexity Perspective. AGU, pp. 345–359.

SAEFL, (2003) Guiding Principles for Swiss Watercourses: Promoting sustainable watercourse management. SAEFL/FOWG, Bern.

Schneider, S.H., Kuntz-Duriseti, K., (2002) Uncertainty and Climate Change Policy, in: Schneider, S.H., Rosencranz, A., Niles, J.O. (Eds.), Climate Change Policy: A Survey. Island Press, Washington D.C.

SFOE, (2012) Statistique des amènagements hydroélectriques de la Suisse. Swiss Federal Office of Energey, Ittigen, Switzerland.

Smith, P.C., Calanca, P., Fuhrer, J. (2012) A simple scheme for modelling irrigation water requirements at the regional scale applied to an Alpine river catchment. Water 4, 869-886.

Smith, P.C., Heinrich, G., Suklitsch, T., Gobiet, A., Stoffel, M., Fuhrer, J. (subm) Irrigation water requirements in the Swiss Rhone catchment under climate change: Station-scale bias correction and uncertainty analysis. Climatic Change submitted, 2013.

Stoffel, M., Huggel, C. (2012) Effects of climate change on mass movements in mountain environments. Progress in Physical Geography 36, 421–439.

Stoffel, M., Bollschweiler, M., Beniston, M. (2011) Rainfall characteristics for periglacial debris flows in the Swiss Alps: past incidences – potential future evolutions. Climatic Change 105, 263–280.

Stoffel, M., Mendlik, T., Schneuwly-Bollschweiler, M. Gobiet, A., (in press) Possible impacts of climate change on debris-flow activity in the Swiss Alps. Climatic Change. doi:10.1007/s10584-013-0993-zValais, (2009a) Informations Statistiques: Office de statistique du canton du Valais. Available at: http://www.vs.ch/Navig/navig.asp?MenuID=16556&RefMenuID=0&RefServiceID=0 (accessed on 9 June 2009).

Valais, (2009b) Plan d'aménagement de la 3ème correction du Rhône - PA-R3. Available at: http://www.vs.ch/Navig/navig.asp?MenuID=16520&RefMenuID=0&RefServiceID=0 (accessed 28 July 2009).

Wilby, R.L., Orr, H., Watts, G., Battarbee, R.W., Berry, P.M., Chadd, R., Dugdale, S.J., Dunbar, M.J., Elliott, J.A., Extence, C., Hannah, D.M., Holmes, N., Johnson, A.C., Knights, B., Milner, N.J., Ormerod, S.J., Solomon, D., Timlett, R., Whitehead, P.J., Wood, P.J. (2010) Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation principles into practice. Science of The Total Environment 408, 4150-4164.