



ACQWA

AWQWA

Assessing Climate impacts on the Quantity and quality of WAter

A large integrating project under EU R&D Framework Programme 7 (FP7)



UNIVERSITÉ
DE GENÈVE

ACQWA



ACQWA Science and Policy Brief

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Assessing Climatic change impacts on the Quantity and quality of WAter
(A large integrating project under EU-FP7, 2008-2013)

A Science and Policy Brief

*Document compiled by the ACQWA Coordination team
University of Geneva, Switzerland*

August 2013

ACQWA Project Partners

37 partners, 30 academic and research organizations, 10 countries



The “Jet d’Eau”, one of Geneva’s famous landmarks. The University of Geneva was home to the ACQWA project coordination from 2008-2013

Switzerland

- UNIGE: University of Geneva (Coordination + 4 teams)
- UNIBE: University of Bern
- ETHZ: Swiss Federal Institute of Technology, Zurich (3 teams)
- Agroscope (Federal Agricultural Research Institute), Zurich-Reckenholz
- IHEID: Graduate Institute for International Research and Development, Geneva (2 teams)

Italy

- ICTP (International Centre for Theoretical Physics), Trieste
- UNIAQ: University of l’Aquila
- ARPAPMNT (Regional Environmental Protection Agency), Piemonte
- ARPAVDA (Regional Environmental Protection Agency), Valle d’Aosta
- CVA: Compagnia Valdostana dell’Aqua
- Fondazione Montagna Sicure, Valle d’Aosta
- ENEL (State Electricity), Rome
- ISAC-CNR (Institute for Atmospheric Sciences and Climate), Turin
- POLIMI: Politecnico di Milano
- PNGP (Gran Paradiso National Park)
- MONTEROSASTAR (Cable-car company), Macugnaga
- RSE (Ricerca sul Sistema Energetico), Milan

Spain

- IPE-CSIC (Institute for Pyrenean Ecology), Zaragoza

France

- CNRS: Centre National de la Recherche Scientifique (1 partner in Paris, 2 partners in Grenoble)
- CEN (Centre d’Etudes de la Neige), Grenoble
- LSCE (Laboratoire des Sciences du Climat et de l’Environnement), Paris

Germany

- MPI: Max-Planck-Institute for Meteorology, Hamburg

Austria

- UNIGRAZ: University of Graz
- BOKU: University of Vienna (Bodenkultur)

UK

- BHAM: University of Birmingham
- UNIVDUN: University of Dundee

Chile

- CEAZA (Centre for Arid Zones Research), La Serena
- CECS (Centre for Scientific Investigations), Valdivia

Argentina

- ITDT (Instituto Torcuado di Tella), Buenos Aires

Kyrgyzstan

- KNAS: Kyrgyz National Academy of Science, Bishkek



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El Juncal, Chile

The elevation of the summit of this glaciated mountain is 6,200 m above sea level. It is the source of the Aconcagua River, one of the ACQWA project case-study regions.



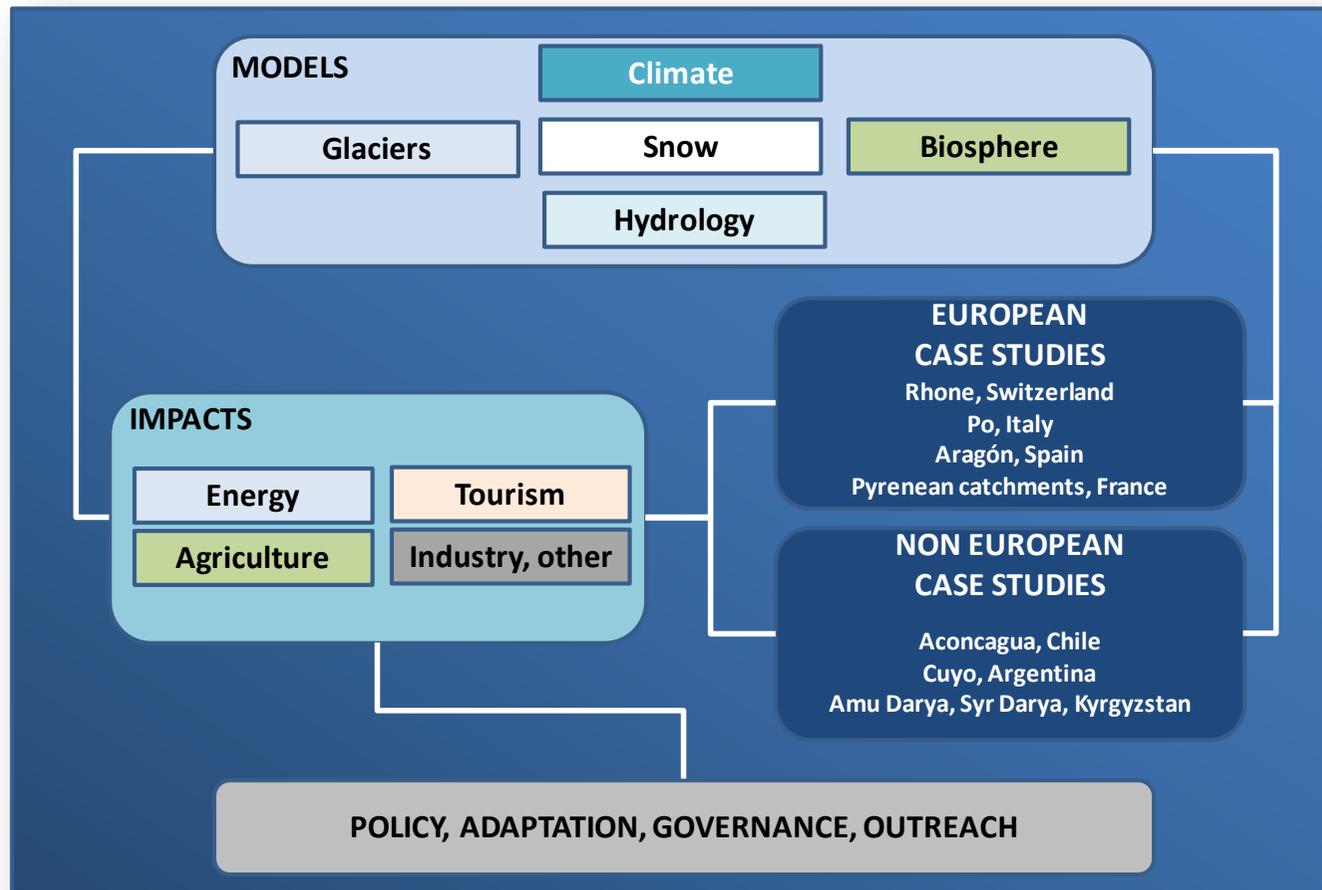
Foreword

The ACQWA project was formulated in response to the first call for climate-relevant projects under the EU 7th R&D Framework Programme (FP7). The philosophy of the project was based on the need to accurately assess the vulnerability of water resources in high-elevation, mid-latitude populated mountain regions. In such regions, declining snow and ice in a warmer climate are likely to strongly affect hydrological regimes, in terms of quantity, seasonality, and also quality. As a consequence of changing water availability, both upland and populated lowland areas will be affected. Rivalries and conflicts of interest may emerge as economic sectors such as agriculture, tourism or hydropower compete for water that may no longer be available in sufficient quantities or at the right time of the year for these sectors to function. The challenge for the ACQWA project was thus to estimate as accurately as possible future changes in order to prepare the way for appropriate adaptation strategies and improved water governance. The project has enabled a suite of state-of-the-art models to be applied, adapted, or developed to address many of the issues related to a changing physical world and to the socio-economic impacts that these changes will inevitably generate. Model results have also been used to assess how robust current water governance strategies are and what adaptations may be needed to alleviate the most negative impacts of climate change on water resources and water use.

The ACQWA project has been coordinated by the University of Geneva since its inception in October 2008, and indeed is one of the largest climate-related projects coordinated by Switzerland under FP7, both in terms of funding and the number of partner institutions (30 in 10 countries for a total of 37 different research, public, or private research entities). Such an endeavour was in itself both a scientific and an administrative challenge. However, the excellence of the consortium provided sufficient motivation for both the Coordination and the research teams to move forward collectively to produce novel results of use to both Science and Policy.

It has thus been a great privilege for us at the Coordination in Switzerland to be involved scientifically and administratively in the ACQWA project, and to view at the end of the five-year funding period the tremendous progress in the knowledge base that observations and models have enabled. As this project comes to closure, it is our wish to see other projects of this nature begin, focusing on the weaker points identified in our project and on the numerous areas of uncertainty that are inherent to complex, interacting systems. It is also with keen interest that we shall follow the developments that may take place, via the European Commission and other national or local authorities, in terms of adaptation and water governance

**Martin Beniston, ACQWA Project Coordinator
Markus Stoffel, ACQWA Project Director
and the ACQWA Project Coordination Team**



Overview of the principal modules of the ACQWA project



Objectives of the ACQWA project

Scientific scope of the ACQWA Project

To assess the **vulnerability** of water resources in **mountain regions** where snow and ice are a major component of the hydrological cycle

- Water in these regions will be vulnerable in a warmer climate because of reduced volumes of snow and ice

To use, refine, and develop **numerical models** to help understand interlinks between climate system components:

- climate, hydrology, snow and ice, vegetation

To predict the evolution of these systems over the next **50 years**

- a mid-century time horizon is closer to targets that are useful for water managers and policy-makers compared to 2100

Policy-relevant issues within ACQWA

An assessment of the potential **impacts** on:

- Extreme events
- Energy
- Agriculture
- Aquatic ecosystems
- Mountain forests
- Tourism

Identification of possible **rivalries** among **economic actors**, in the context of a resource that may become rarer in a warmer climate

- To assess how such conflicts could be resolved through improved governance

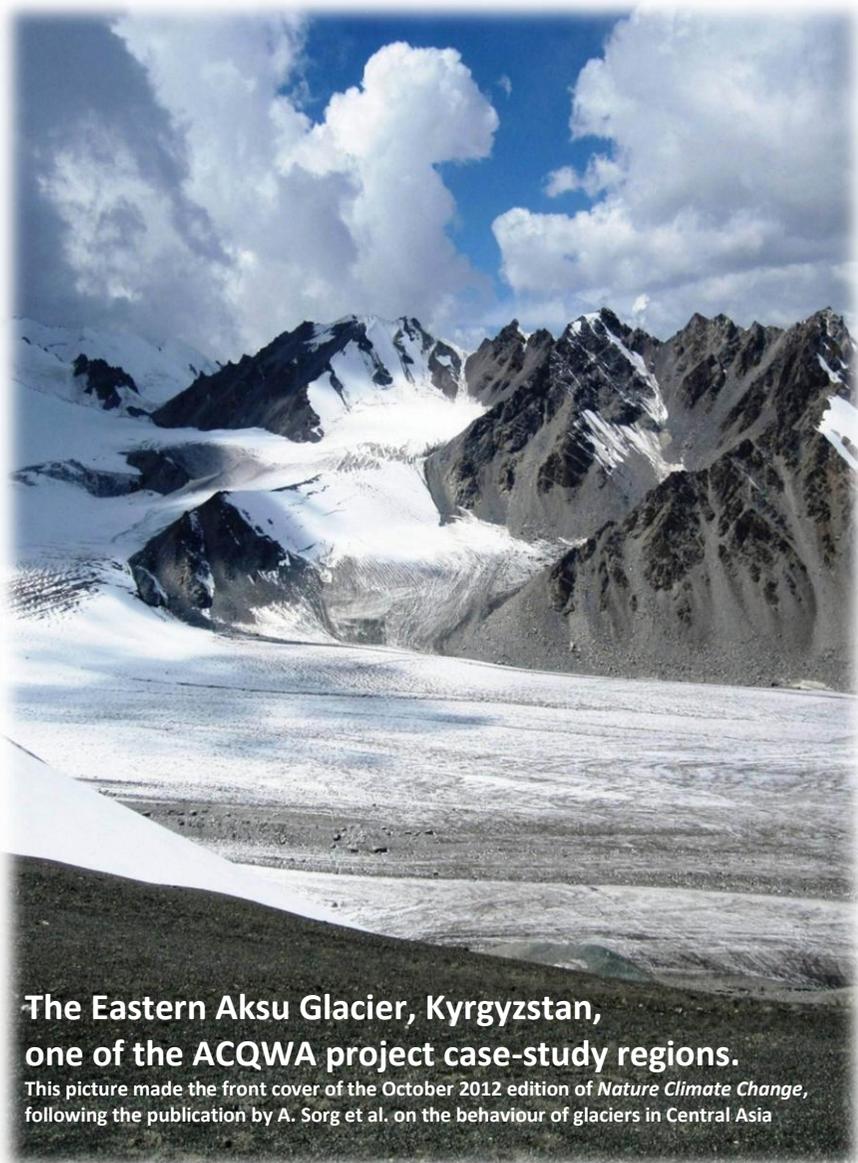
Proposals for adaptation options in order to minimize the more adverse climate-generated **risks**

Understanding the **upstream-downstream** (in terms of water) and **upland-lowland** (in terms of economic development) **implications of changing water resources** originating in mountains as a key to **successful adaptation options**

Policy-relevant research within ACQWA

Climate change will likely modify **seasonal** and **overall water availability** and, as a result, there will be increased competition for water. As a consequence, the ACQWA project has a number of **policy-relevant deliverables** that are summarized in this document, based on the modelling work that enables an overall assessment of changes in water availability and the resulting impacts. The **policy deliverables** strive to:

- **Present** different policy options and analysis of their respective costs and benefits to individual sectors and to Society as a whole, in different regions.
- **Determine** how regulatory frameworks for water distribution among sectors and groups may be under pressure because of increased competition for water, and the changes in water governance that may be necessary.
- **Compare** water governance within the European Alps with that of other regions (Central Asia; Chile and Argentina), where political and economic structures are different from Europe.
- **Assess** the policy choices that can be envisaged within the legal environment in which such policies are implemented, through an analysis of the applicable law relating to integrated water resources management (e.g., the EU Water Framework Directive, the 92 UN ECE Helsinki Convention, as well as various national, provincial, and local legislations).



**The Eastern Aksu Glacier, Kyrgyzstan,
one of the ACQWA project case-study regions.**

*This picture made the front cover of the October 2012 edition of *Nature Climate Change*, following the publication by A. Sorg et al. on the behaviour of glaciers in Central Asia*



**The rapidly-receding snout of the Rhone Glacier,
In Central Switzerland.**



PART 1

SUMMARY, METHODS, MODELS, AND CASE-STUDY REGIONS



Summary of main Policy Implications

Comprehensive, sustainable, transformational adaptation

ACQWA has developed climate information for a set of mountain regions downscaled to temporal and spatial scales that are intended to be more useful to the challenges decision makers face. Climate change impacts in a number of basins dominated by snow and ice show that water managers and users will need to adapt to change in the quantity and timing of water resources. This is not only relevant to local and regional scales, but also to communities and economic sectors downstream who are reliant on a range of goods from mountain regions and their resources (e.g. electricity, water, water storage in the form of ice and snow).

A certain level of uncertainty has always existed in water resources planning due to climate variability. Climate change represents an increase in uncertainty and the speed and magnitude of change. Water policy and management frameworks therefore must manage and cope with both existing and increasing levels of uncertainty from climate variability and climate change impacts. **While principles in the management, conservation and adaptation of water resources and ecosystems abound, there remains a lack of clear policy guidance on practical governance mechanisms and actionable measures, especially in the context of mountain areas.**

Synergies or conflicts across different sectoral policies are particularly relevant in mountain areas, where fragile ecosystems provide valuable economic services such as energy for hydropower, water towers and natural storage systems of water,

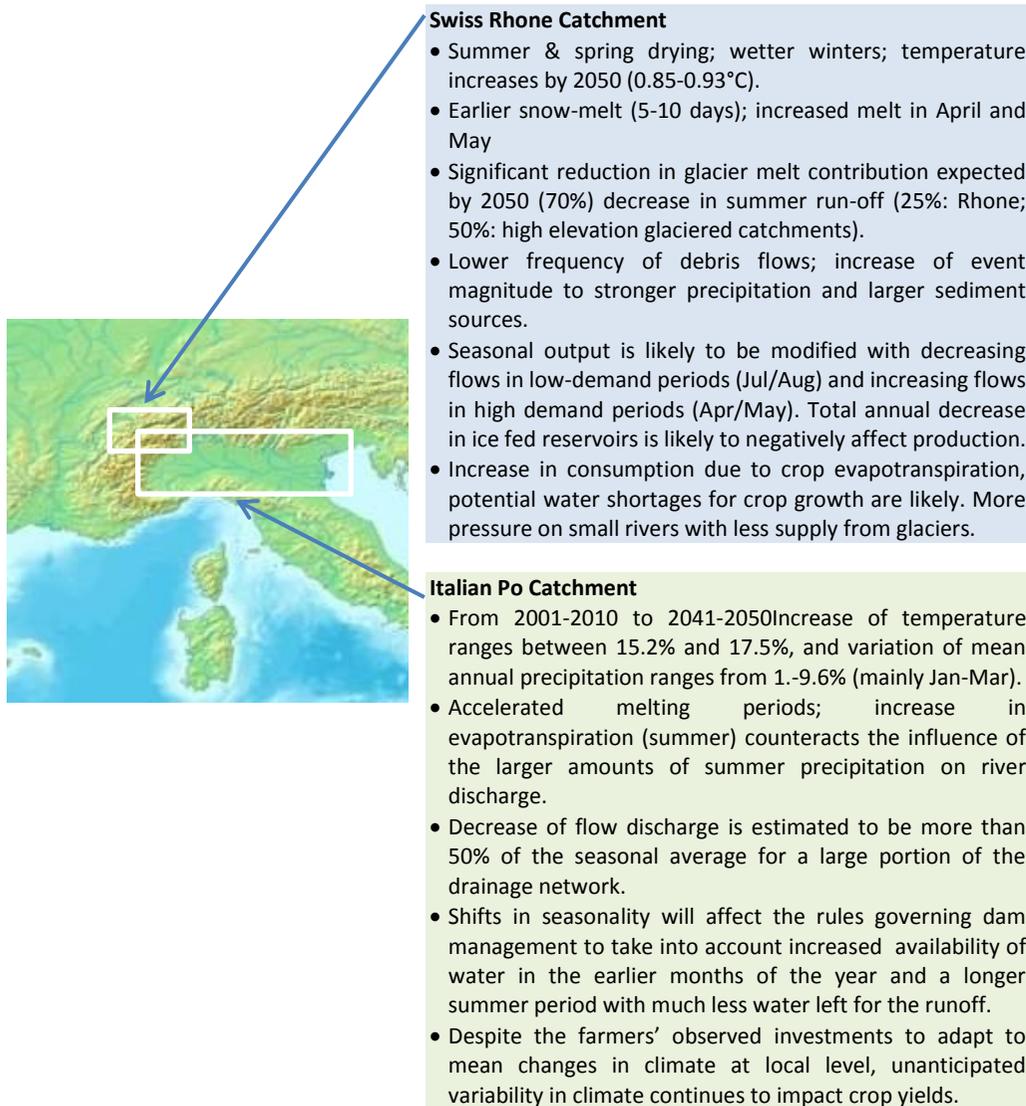
tourism uses, etc. Existing tensions across sectors, governance scales and actor groups are likely to be further heightened by impacts from climate change, underlining the need for not only integrative but also adaptive water resources governance and management. In the highly sensitive and complex environments of mountain areas, known as 'sentinel sites' in their early responses to climate change, adaptation options tend to be limited in comparison to lowland areas.

ACQWA policy work therefore focused on:

- *identifying underlying water governance challenges in the mountain case regions;*
- *assessing adaptive capacity of these regions;*
- *identifying practicable governance mechanisms and actionable measures for the operationalization of adaptive and integrative water resources management and governance principles, specifically for the alpine context.*

Climate change in the mountain regions studied are leading to modifications in quantity and timing of water resources that have potentially significant ramifications for water governance and management. Water managers will need to adapt to potential increases in runoff in late winter and autumn and potential decreases in spring and late summer. Snow melt is likely to take place earlier, with increased melt in spring, 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** that will have repercussions for the management of hydropower reservoirs. At present, glaciers and snow pack provide a valuable buffer of additional water during dry summers. While increased glacial runoff from melting glaciers will at first lead to surface runoff surpluses, **continued reductions in glacier volume will eventually result in a decrease of summer runoff.** In some of the ACQWA case areas, this phenomenon is already occurring.

Climate change impacts in the ACQWA case-study regions



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.



Amu Darya, Syr Darya, Kyrgyzstan

- 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 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 use. 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 up to 14%

Figure 1: ACQWA project case-study regions and associated climate impacts

Base maps: © Demis World Map Server
www2.demis.nl/mapserver/mapper.asp



Enabling framework for adaptability to climate change in an Alpine context

Adaptation policy needs to be sensitive to the challenges of spatial (local-national) and temporal scales (short – long term; climate variability – climate change). This is particularly important in mountain regions where highland ecosystems provide goods and services to lowland areas, economic imbalances persist across highland-lowland scales, multiple sectors compete for water resources at different seasonal points, and the impacts of climate change are likely to be acute. Water governance and management will therefore need to minimize trade-offs across different sectoral requirements and not degrade **resilience** at other scales, **avoiding lock-ins** (rights, infrastructure, land-use planning, economic, water requirements, energy mixes) with **expensive reversal costs**.

- Water governance (systems and rules in place that affect the use, protection, delivery and development of water resources) and 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.
- An adaptable water management and governance regime must not only manage current baseline uncertainty levels of climate variability (e.g., stochasticity of precipitation) but also the more unpredictable forms of un-

(e.g. shifts in seasonality as glaciers melt)

- Water managers need to be able to make decisions under uncertainty, in their application of rules and the operationalization of policy for the practical aspects of water allocation and protection, as well as protection from and during extremes.

certainty arising from climate change

- Actionable measures that operationalize these principles are required in order to alleviate underlying tensions that are likely to be exacerbated by climate change impacts.
- Infrastructure will need to be robust to flows of a larger range than prior climate conditions, but which in itself will be highly uncertain. Infrastructure design should therefore account for natural climate variability and change through stochastic approaches that examine multiple possible trajectories.
- Technical adaptation should prioritize no-regret, reversible, flexible and iterative actions, that take a long term and ecosystem based approach (rather than purely grey infrastructure based) and integrate both adaptation and mitigation requirements.
- Multi-goal infrastructure should also be developed for redundancy, dynamism, uncertainty or enhanced benefit across the social and ecological system.

Identifying and alleviating exacerbation points

Governance and management challenges: common lessons drawn across the ACQWA basins

- **Fit:** The scale at which water is managed (user/management) can block longer term catchment scale planning and smoothing over shifts in seasonality creating critical local situations.
- **Sectoral focus:** The lack of integrative water and adaptation planning at catchment or basin levels. Policy goals may be integrative, but divisive in implementation/management.
- **Lock-in:** The legacy of technical and grey infrastructure and spatial planning (concreting of river reaches, removal of river bed, building zones in floodplains, commitment to single economic sectors, focus on specific species

conservation, etc.) leads to a decrease in resilience as baseline conditions change; Fixed and long term of concessions or rights that do not account for impacts on hydropower production and timings.

- **Rules and incentives:** Lack of formal rules on certain uses; New, un-regulated uses (e.g. increasing use of snowmaking; Lack of demand management integrated into spatial planning; Lack of formal mechanisms to manage competition across catchment areas.

Developing adaptive capacity to respond to challenges of uncertainty and climate change impacts

Water governance will need to not only overcome the challenges laid out above, but do so in a way as to include climate variability and prepare for climate change, by balancing the requirements for structure and predictability at higher governance scales with the flexibility at lower scales to react at lower governance scales.

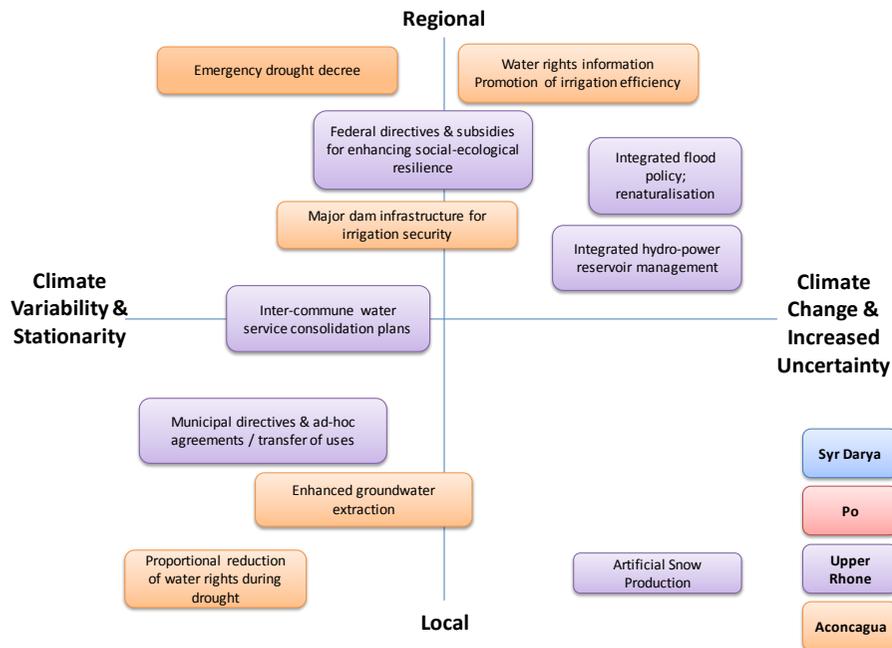
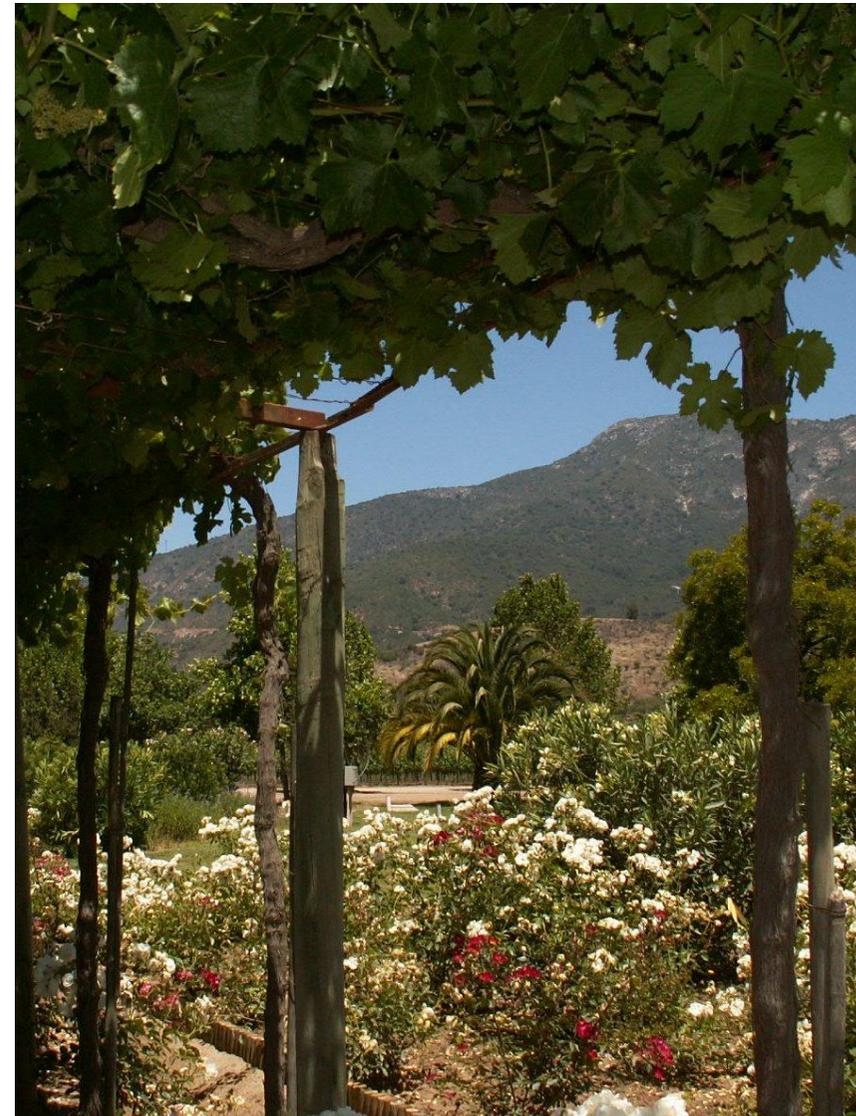


Figure 2: Plotting adaptive capacity according to temporal and spatial scales



Grapevines in the Aconcagua basin near Santiago de Chile



From adaptive principles to governance mechanisms in policy and legislation

Policy makers and managers must not only better manage previous levels of hydro-climatic variability but also a wider envelope of variability and uncertainty associated with climate change. Table 1 presents a means of framing the adequacy of different available governance mechanisms to cope with these different scales of uncertainty.

	Stationarity with predictable uncertainty	Broader uncertainty with reduced predictability	Irreversibility and Regime shifts
Review Periods	Assessment of outcomes.	Inclusion of climate data.	Incorporate climate scenarios.
Varied rights	Equitably match demand to supply.	Vary use rights in advance of expected changes.	Manage larger shifts in timing or volume of availability.
Time limited licencing/permits	VARIABILITY MORE IMPORTANT IN SHORT TERM.	MUST BE SUBJECT TO VARIABILITY.	Maximum duration of the permit will influence the usefulness.
Entitlements as share of overall resource	Annual allocation based on expected resource availability	Integrate climate projections for review and revision of long term planning framework.	Reduce the proportion of the resource that is available for use.
Water rights trading	Distributing rights in areas or times of limited availability.	CHALLENGES OF SPECULATION AND PRIORITISATION OF DIFFERENT USES.	LESS EFFECTIVE AT ADDRESSING VARIABILITY.

	Stationarity with predictable uncertainty	Broader uncertainty with reduced predictability	Irreversibility and Regime shifts
Administrative requirements	For basin management, appropriate user involvement, use cadastres.	Use cadastres at multiple scales, reinforce compliance and integrate emerging science.	<u>STRONGER REQUIREMENTS FOR</u> integration of emerging science and impact scenarios.
Qualitative and quantitative standards	Guide short-term permit variability requirements and abstraction controls.	Variability critical, but in context of combined approach.	Reactive variability and integration of new conditions required.
Locally appropriate standards	Appropriate for guiding short-term use right variability.	SECONDARY BASIN/LOCAL SPECIFIC LEGISLATION USEFUL, NOT IMPERATIVE.	Primary legislation may be more relevant for larger variability.
Monitoring standards	VITAL TO ENSURE NETWORK FUNCTIONING, AVAILABILITY AND EXCHANGE.	Fundamental to the integration of climate data.	Fundamental to the integration of climate scenarios and data.
Sector Coordination	ADDRESS MANAGEMENT CONCERNS IN DEMAND MANAGEMENT.	Inter-sectoral planning under shifting water availability patterns.	Inter-sectoral coordination crucial to effective adaptation under regime shifts.
Consultation process	PROMOTE AND IMPLEMENT equitably-applied variation.	ESTABLISHES TRUST TO SMOOTH IMPLEMENTATION OF ADAPTATION MEASURES.	Consultation and trust essential for preparing for future scenarios that may not be perceived to be imminent.

Table 1: Possible pathways to alleviate risks associated with climate impacts

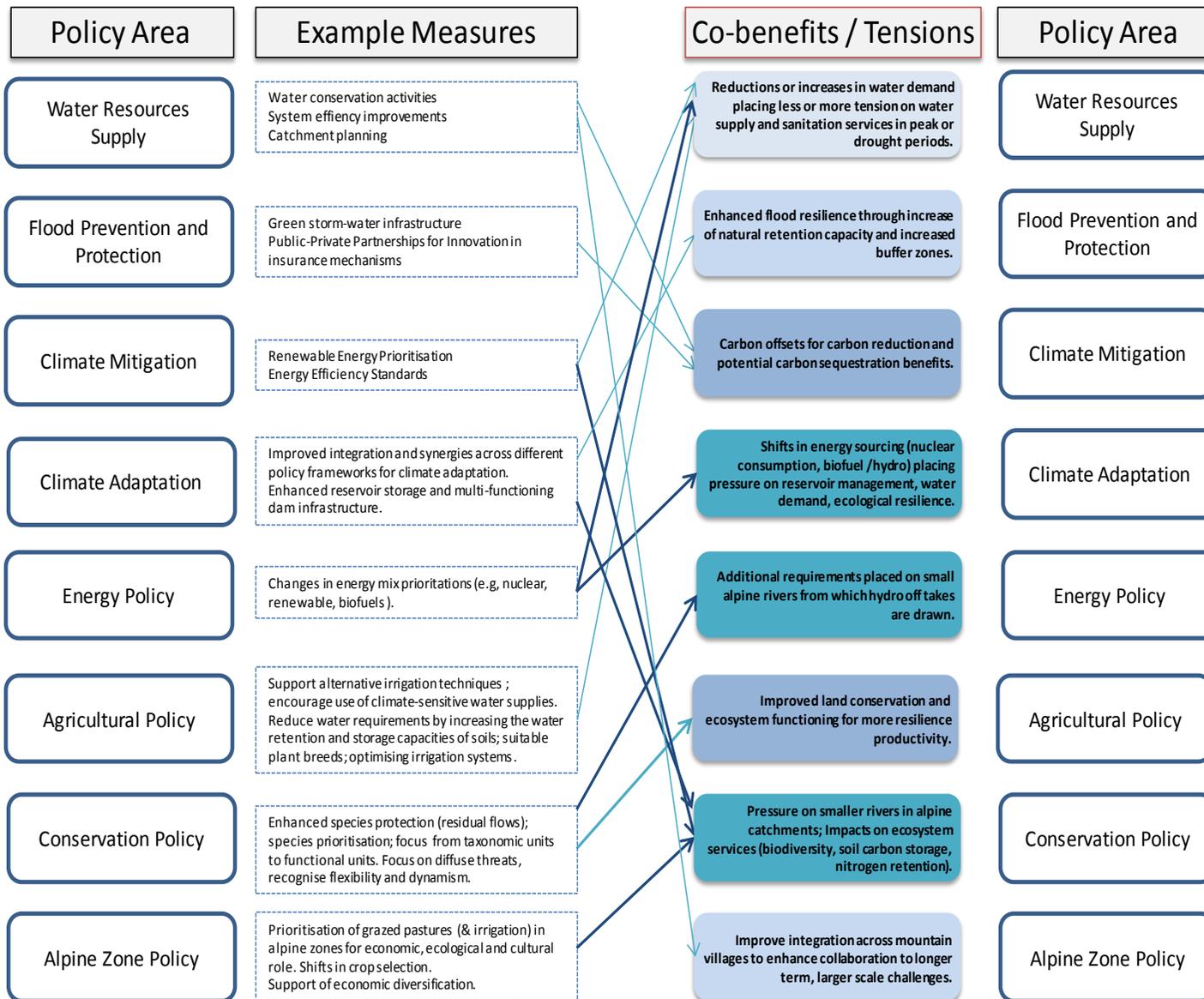


Figure 3: Actions and policies to optimize decision-making in the face of climate impacts

Many challenges in developing adaptive capacity relate to challenges of vertical and horizontal integration, where flows of knowledge and data, rules and plans, formal and informal institutions, policy goals and local or regional laws, plans and priorities are not aligned across governance scales or natural boundaries to either fulfill management goals or prepare for emerging challenges. This is particularly important in mountain regions, where multiple sectors (hydropower, tourism, agriculture, domestic supply, mining or other industries) operate across a catchment, but geographical and political boundaries are often not aligned. Policies may be vertically integrated through frameworks such as strategic or environmental impact assessments, or horizontally integrated by formal and informal institutions (e.g., river basin management organizations, user groups). Figure 3 provides some examples of how specific actions and policies would optimise multiple benefits across conservation – adaptation – mitigation policy spheres.



Methods and Models

SUMMARY OF KEY FINDINGS

- Data from the EU/FP6 “ENSEMBLES” Project (www.ensembles-eu.org : the highest standard regional climate model simulations currently available) were used for climate simulations at a spatial resolution of 25 km for European domain, using the IPCC A1B emissions scenario.
- Improved of regional climate simulations (grid spacing 25 km, effective resolution 100 km) were applied in order to better model hydrological processes in complex alpine terrains (grid-scales of a few 100 metres) by correcting errors, focusing on downscaling, and creating high resolution data for greater Alpine area until 2050.
- A 2°C warming is projected by 2050, most prominent above 1500 m elevation in autumn.
- Precipitation may increase in winter and decrease in spring and summer.
- Decrease in snow depth is projected to be most visible in winter and spring.
- Extremes events: Higher frequencies of precipitation event occurrences are projected as well as more separate wet periods within events, with shorter durations but higher intensity.



Model-simulated climate baselines

Data from the EU/FP6 “ENSEMBLES” project (www.ensembles-eu.org) have been made available to the ACQWA-partners to drive different impact models. For the ENSEMBLES project, the participating climate modeling institutes performed simulations with different regional climate models at a spatial resolution of 25 km for the European domain. The regional climate models were driven at the lateral boundaries by ERA40 reanalysis data for the period 1951 to 2000 for the purpose of validation.

Moreover, future climate simulations have been performed for the IPCC A1B emissions scenario using different global climate models to force the regional climate models within the frame of ENSEMBLES.

Climate scenarios tailored for climate change impact analyses in the Alpine region

The basis for the assessment of climate change impacts on the quality and quantity of water in ACQWA are regional climate simulations from the EU FP6 project ENSEMBLES. Though the ENSEMBLES simulations currently represent the highest standard of quality in regional climate modeling, their direct application in hydrological modeling (or climate change impact research in general) is not advisable due to remaining model errors (see Figure 4) and the scale gap between climate models with a grid spacing of 25 km (i.e., an effective resolution about 100 km) and most hydrological models (operating at grid-scales of a few 100 meters). Therefore, ACQWA has a strong focus on further downscaling and error correction of regional climate simulations.

The entire ENSEMBLES multi-model dataset has been post-processed using an empirical-statistical technique (quantile mapping, or QM) to remove errors the mean and variability from daily temperature and precipitation time series. Figure 4

illustrates the QM method. It is capable to remove model biases and to adjust the variability without removing the climate change signal in variability. In addition, QM proved to be very robust over a wide range of applications and to perform equally or superior to methods like the analog method, local scaling, or multiple linear regressions.

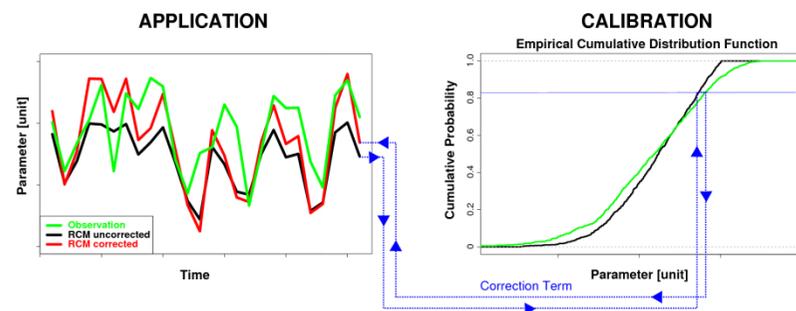


Figure 4. Quantile mapping: Modeled cumulative frequency distributions are mapped to observed distributions (right). Mean and variability of modeled time series are adjusted, but time correlation with observations is only slightly improved (left). Applied to climate scenarios, this drawback is irrelevant, but advantages remain and changes in not only mean climate but also in variability and extremes can still be studied after correction.

In ACQWA, QM is implemented in a way that it properly accounts for spatially and seasonally varying model errors. Figure 5 demonstrates the performance of QM over the Alpine region. As observational basis, the E-OBS dataset (v2) has been used and the results are available on a 25 km grid. Two examples of uncorrected (left panels) and corrected (right panels) summer temperatures from RegCM3 (upper panels) and precipitation from REMO (lower panels) are shown. Seasonal mean errors are reduced by at least half an order of magnitude.

The simulations shown in Figure 5 (extended until 2050) form the basis for larger scale climate change impact investigations in ACQWA. However, in order to satisfy the need for local scale climate information, daily and three hourly climate scenarios at the location of meteorological stations are produced in addition. The station-scenarios include further parameters like radiation, humidity and wind

speed (depending on data availability and user request) and are the basis for most local scale climate change impact simulations in ACQWA. A throughout evaluation of this station is based on a multi-variable bias correction method.

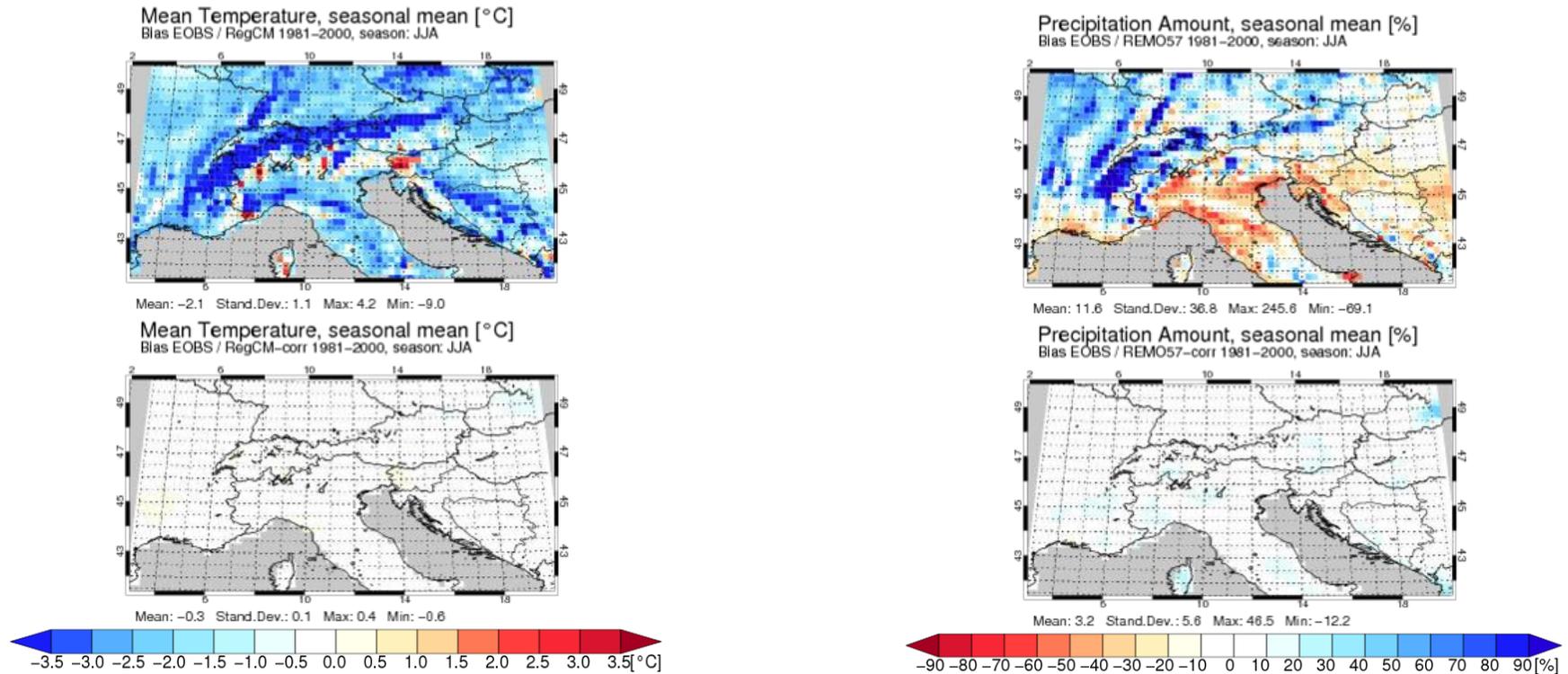


Figure 5. Seasonal errors in regional climate models before (left panels) and after empirical-statistical correction (right panels): RegCM3 summer temperature (upper panels) and REMO summer precipitation (lower panels). Training period for the empirical-statistical correction: 1961 – 1990; evaluation period: 1981 – 2000.



Regional climate model simulations

For the complex alpine terrain the resolution of the ENSEMBLES data of 25x25 km² is rather coarse. The climate change signal may be biased due to insufficient representation of the structured Alpine topography. Therefore high-resolution climate change information was created for the greater Alpine area for the future period until 2050, to get a better representation of the terrain features. In the framework of ACQWA, we conducted a 100 year long climate model simulation with the regional climate model REMO in 10x10 km² horizontal resolution.

The results have been compared with observations and projected climatic changes have been analyzed. According to the IPCC A1B scenario, the entire region will face a warming up to 2°C, which is most prominent above 1500m and in fall. Related to this are changes in total precipitation, which might increase in winter, but are projected to decrease in spring and summer months.

The snow depth is influenced by many factors, some of which are related to the amount to falling snow in the different seasons, but also the melting due to increased temperatures. For mountainous regions in the Alps, which are higher than 1500 m, a strong decrease in snow depth is projected and mainly visible in winter and spring.

A number of studies reveal that the land surface representation in climate models plays a vital role in the quality of the modeled climate. A change in the so called land surface scheme, which parameterizes the physical processes at the Earth's surface, will mainly lead to differences in the exchange between surface and atmosphere due to modifications in heat, moisture and momentum fluxes. Mesoscale atmospheric circulation can be influenced by the representation of stomatal conductance, because of the important control on the Bowen ratio. Modifications in model surface schemes alter the modeled climate.

Within the ACQWA framework, the land surface scheme of REMO was improved by

coupling REMO to a 3rd generation land-use scheme (JSBACH), which includes a process-based representation of evapotranspiration due to the fact that it simulates plant photosynthesis and its control on stomatal conductance explicitly. The dynamic coupling of REMO and JSBACH to the new generation regional climate system model REMO with interactive Mosaic-based Vegetation (REMO-iMOVE) introduces an interactive vegetation model to the regional climate model. In REMO-iMOVE, vegetation processes can influence atmospheric processes and vice versa and thus, also non-linear feedbacks can be simulated.

First simulations show that the new developed model version REMO-iMOVE, is able to simulate the European climate in the same quality as the standard REMO does. The occurring differences reveal the influence of the surface schemes on the modeled climate, which can be distinct in some regions.

Local-scale climate information.

Overview: A methodology to downscale climate model outputs to local and catchment scales by means of a stochastic model has been developed to generate spatially distributed stochastic precipitation and temperature climate scenarios at the sub-daily temporal scales in a multisite and gridded fashion. The methodology represents a robust, efficient and unique approach to generate ensembles of time series of spatially distributed hourly precipitation scenarios using Monte Carlo simulation techniques. It presents a unique alternative for addressing the internal variability of precipitation processes at high temporal and spatial resolution, as compared to other downscaling techniques, which are affected by both computational and resolution problems.

The investigations on the future changes in both precipitation and temperature extremes showed that the changes might be different in sign and magnitude at different temporal scales. This contrasts with the majority of the available studies that simply predict a generalized increase of extremes, regardless of the temporal



scale and of the return period. Accordingly, conclusions based on the analysis of future scenarios at daily or longer scales may not apply for shorter durations. Moreover, it has been observed that downscaling GCMs or RCMs leads to significantly different behaviour in the change on the extremes. Indeed, the downscaled temperature series driven by the GCM ECHAM5 lead to larger increase on the warm temperature extremes than in case of the simulations forced with the RCMs. Conversely, the downscaled precipitation series forced with the RCMs lead to larger change on precipitation extremes than in case of the simulations forced with the GCM. The more accurate representation of the orography by the RCMs and the improved capability in capturing the precipitation extremes compared to the GCMs might be the reason for a different climatic signature driving the re-parameterization of the stochastic downscaling model.

In terms of structural changes in precipitation, compared to the present conditions, the stochastically downscaled scenarios yield to a precipitation patterns with a higher frequency of event occurrences, but with more separated wet periods within each event. In addition, each of these wet periods should have shorter durations, higher intensity, and they would be likely more localized and spatially sparse. The analysis of the changes of statistical properties across a broad range of temporal scales indicates that uncertainty due to the internal variability of the precipitation process, investigated as the spread of the Monte Carlo simulations, is in most of the cases larger than the variability determined by different climate models. No overall general pattern and no pattern dependent on the location or elevation of the station are observed; rather, changes are highly variable in space. This indicates the highly uncertain and sensitive character of precipitation changes, and therefore, the appropriateness of stochastic downscaling to account for the uncertainty related to the internal climate variability. It is interesting to observe that the changes in the variance are in some cases of similar order of magnitude of those in the mean, and in other cases, even larger, thus suggesting a tendency to more frequent occurrence of large deviations from the mean. In addition, the spatial variability of the hourly variance changes is much larger than the corresponding variability of the mean.

In terms of distributional properties, hourly aggregation of the future marginal distributions present a very similar shape compared to the control simulations, with steeper tails occurring only in wet climatic conditions. But, for temporal aggregations equal to or larger than 6 hours, all the simulations, regardless of the large scale climate signature, projections agree as to a change in the shape of the distribution, with a tendency to present longer tails in most of the cases. Even though the magnitude of this change is variable in space, this result is consistent throughout the stations in the catchment.

Downscaled simulations of extreme events show some dependence from the climate model driving the re-parameterization of the stochastic model. GCM driven simulations do not appear to exhibit an increase of the stochastic variability, whereas those driven by RCMs show a significant effect on it, with slight decreases for low durations (1 hour) and large increase (30-50%) for higher durations (12 hours and higher). For durations below 6 hours, it seems that the natural variability of climate is comparable to the signal induced by climate change, whereas this is not the case for longer durations. Most of the identified changes are, moreover, statistically significant and seem to be coherent across space. Wet spell durations show an increasing trend, irrespective of the climate model driving the re-parameterization, whereas this does not seem to be the case for the dry spell duration.

Finally, the overall changes in space seem to be remarkable, event at relatively small scales, but they are specific to the case study and suggest that localising climate scenarios by means of downscaling techniques, which provide simulations at high resolution in space and time, is of extreme importance for impact analysis.

Added value from the ACQWA project: The stochastic downscaling methodology was used to generate ensembles gridded precipitation and climate scenarios that allowed to consider the intrinsic variability of present and future climate, thus providing, likely for the first time, a quantification of the uncertainty associated



with the precipitation input to the hydrological models used to quantify the effects of climate change on the hydrologic response of the investigated basins. The ACQWA project was a pioneer in showing how high space-time resolution precipitation scenarios for catchment scale impact analysis can be generated, which not only allow to address the expected changes in the mean signal, but also provide a quantification of the changes affecting variability, statistical and distributional properties as well as extremes at resolutions that are consistent with the technical scales of water resources management.

Policy-relevance of this research: The availability of local and catchment scale precipitation scenarios at high spatial and temporal resolution also simulating their stochastic variability allows to quantify the intrinsic variability of climate scenarios, thus providing a new perspective with regard to adaptation policies, and overcoming the limitations of deterministic large scale climate outputs that are still unable to capture the small scale variability, both in space and time. In particular, the developed methodology represents a unique tool to compare the magnitude of the intrinsic variability for both the present and the future climates, thus providing a measurement of how uncertainty accounting design under stationary conditions allows to develop adaptation strategies even under highly uncertain estimates of future climates.

Biosphere modelling

Overview: A further modelling component of the ACQWA project has addressed the interaction of climate change with the biosphere, consisting in the integration of a dynamic vegetation model (DVM) into the distributed hydrological model used for catchment scale simulations of basin response. The integration was implemented and some preliminary simulations were successfully carried out. The preliminary simulations point at two facts that are of importance in long-term

climate change impact analyses. First, the comparison between the DVM outputs based on the embedded simple hydrology and based on the more accurate water balance simulated by the distributed hydrological model show how poor the hydrological simulations of DVMs are. Since they are often interfaced to climate models, typically to predict the evolution of forest dynamics, these results suggests that their prediction may be unrealistic, as it is affected by a significantly biased soil water balance. Second, the distributed hydrological model integrated by the DVM was able, on the one hand, to mimic some key variables for the analysis of the impacts of climate change on the biosphere, such as the spatial and temporal dynamics of the gross primary productivity and of the leaf area index, and, on the other hand, to produce evapotranspiration patterns that are process based, and, as such more suitable for use in the analysis of the effects of climatic change.

Added value from the ACQWA project: The added value of the above results consists essentially in the demonstration of the huge limitations that characterize DVMs, and of the genuine improvement that integrating (or interfacing) a DVM with the hydrological model allows, especially with respect to soil water balance and evapotranspiration and the related ecosystems services.

Policy-relevance of this research: The preliminary results indicate that a new generation of impact analysis models, which combine distributed hydrological models and DVMs and nevertheless allow long-term simulations at the basin scale, can be formulated, and that their characteristics allow for a more realistic description of the response of the soil-vegetation-water balance to climate forcing. Accordingly, future climate impact assessments which aim at addressing the response of basin vegetation and hydrology to climate change, should consider the use of these combined models for more realistic results of use in decision making processes.

Location of Kyrgyzstan,
Central Asia



The Po Catchment (Italy)
and Rhone Catchment (Switzerland)



The Aconcagua Catchment, Chile



Case-study regions

European alpine catchments

The Rhone and Po river basins in the European Alps have been used as a common “test ground” for model investigations, where the different methodological approaches have converged to the basin scale through appropriate up- or down-scaling techniques. Both basins represent ideal case-study areas, as they comprise all the elements of the natural environment that have been modeled (snow, ice, vegetation, hydrology). At the same time, these are highly regulated watersheds, where economic activities related to hydropower generation, irrigated agriculture, and tourism take place in the context of a climate that is at the borderline between Mediterranean and Continental, and are therefore particularly vulnerable to climatic change.

The boundaries of the Rhone catchment study-area include the alpine segment, running from the Rhone Glacier in Central Switzerland to Lake Geneva. The boundaries of the Po case-study area used in the ACQWA project do always not extend as far as the Adriatic Sea, for reasons of data access and hydrological model constraints. The investigations have thus focused more on the flows from the Alps of Piemonte and Val d’Aosta, with the “ACQWA Po” boundary located at Cremona, on the Po River south of Milan. Regional climate model results, however, cover the entire basin as illustrated in the map on the opposite page.

Outside Europe: The Aconcagua basin in Chile and the Syr Darya/Amu Darya watersheds in Kyrgyzstan

Some of the methodologies developed in the intensive investigations of the European alpine catchments have been applied to the Aconcagua Basin in Chile, where receding glaciers already today pose a genuine threat to water availability.

Investigating the coping strategies of Chilean economic sectors affected by changes in the quantity and seasonality of water resources can help highlight the types of problems that could arise in the Alps in coming decades.

In Central Asia (Kyrgyzstan), the same processes of ice-mass wasting in the headwaters of the Syr Darya or Amu Darya rivers involve much larger glaciers. During the 21st century, the meltwaters from the Tien Shan could in contrast represent a source of economic opportunity, for example through the development of hydropower as a source of foreign revenue.

Other basins

Other research-specific case-study areas comprise the Aragón Basin in Spain for interdisciplinary investigations pertaining to agriculture and energy in a context of changing land-use and climate; and French Pyrenean watersheds for aquatic ecosystem studies in a hydrology, habitat and biota framework. These are located in the Cauterets region in the vicinity of the French Pyrenees National Park.





**A sight that may become increasingly rare by 2050:
vineyards under winter snow cover in the Swiss Rhone catchment**



PART 2

PROJECTIONS OF CHANGE BY 2050

SUMMARY OF KEY FINDINGS

- Stronger warming is expected along the Alpine ridge, especially in summer, with stronger warming in the Western Alps (+1.7°C in winter; 1.9°C in summer)
- Warming is more certain for winter and spring than summer. Choice of global climate model to generate the results has the largest effect on total uncertainty.
- High spatial variability is likely for precipitation with increases in the north of the Alps in spring, summer and autumn, and decreases in southern and western parts.
- Precipitation results have a high level of uncertainty, with regional climate models contributing more than the global models to total uncertainty.

Projected changes: regional climate

Regional climate scenarios for ACQWA and their uncertainty

The basis for the assessment of climate change impact on the quality and quantity of water in ACQWA are regional climate models (RCM) simulations from the EU FP6 project ENSEMBLES (<http://www.ensembles-eu.org/>). Two main simulations have been chosen from the ENSEMBLES multi-model dataset (ICTP_RegCM and MPI_REMO both driven by ECHAM5-r3) and set as mandatory for all impact investigations within the project. In addition, several impact studies have used the entire ENSEMBLES dataset in order to cover climate induced uncertainties more completely. Before using these scenarios as input for impact models, biases have been removed.

In order to facilitate the interpretation of the studies using only two scenarios, these two simulations were put into the context of all available simulations provided by ENSEMBLES project. In ENSEMBLES, a set of 22 high resolution regional climate model (RCM) simulations until the middle of the 21st century was produced (see Figure 6). The simulations have a horizontal grid spacing of about 25 km and the lateral boundary conditions were provided by eight different global climate models (GCMs). Due to limited computational resources, not all possible GCM-RCM combinations could be realised. The simulation matrix mainly addresses boundary conditions (GCM) and RCM uncertainty. Natural variability is implicitly accounted for via the use of different GCMs, but uncertainty due to assumptions on future GHG emissions are not included. However, the restriction to only the A1B emission scenario is of minor importance since the uncertainty due to the choice of the emission scenario is rather small until 2050. As can be seen in Figure 6, the ENSEMBLES simulation matrix is unequally filled and reveals that the majority of RCMs have been forced by the two GCMs ECHAM5-r3 and HadCM3Q0 (10 out of 22

simulations). Therefore, those two GCMs are overweighed compared to other GCMs and ensemble mean climate change signals (CCSs) of the raw simulation matrix are potentially biased towards the climate sensitivity of these two GCMs.



Figure 6. The GCM-RCM simulation matrix of the 25 km simulations for a 2050 time horizon of the ENSEMBLES project. The cells highlighted in orange are the available simulations. The values indicate the simulated and reconstructed changes in summer air temperature for the greater Alpine Region.

To avoid biased estimates, a data reconstruction technique was applied in order to fill the missing elements of the simulation matrix. Furthermore, the reconstructed CCSs were used to calculate a balanced analysis of variance (ANOVA) concerning the two factors GCM and RCM in order to quantify their relative contribution to the overall uncertainty.

Concerning temperature change, the multi-model mean climate change signals reveal a stronger warming along the Alpine ridge, especially in summer. The high sensitivity of the Alps becomes even more evident in the rather small ACQWA region in the Western Alps with projected median warming of +1.7°C and + 1.9°C in winter (DJF) and summer (JJA), respectively.

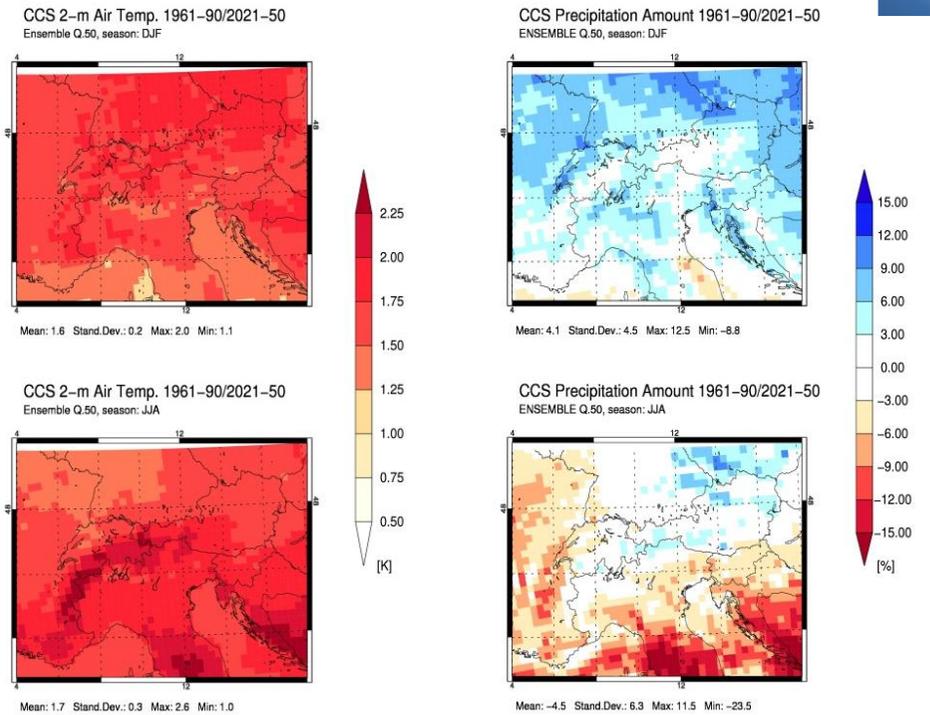


Figure 7 Median of the changes in winter and summer 2-m air temperature (left) and precipitation amount (right) for the 22 ENSEMBLES simulations between 2021-2050 and 1961-1990 in the Alpine region.

The warming is projected by all models of the dataset in all seasons. A more detailed analysis of the distribution of the climate change signals (CCS) (Figure 7), reveals that the uncertainty, is larger in JJA and autumn (SON) compared to DJF and spring (MAM). Further, Figure 7 shows that the two mandatory simulations of ACQWA are cooler than the average, particularly in winter. The variance decomposition for temperature (not shown) reveals that the choice of the GCM has by far the largest effect on the total uncertainty, contributing more than 75 % to the overall variance in most cases. For precipitation, a distinct impact of the Alpine ridge on the spatial distribution of the projected changes exists (Figure 7, right).



The median of the distribution indicates an increase of precipitation north of the Alps in MAM, JJA, and SON, while the southern and western parts indicate a decrease (not shown). Along this transition the changes are highly uncertain. For the small scale ACQWA domain, which is located within the transition zone, very small median precipitation changes are found (Figure 8; median decrease of -1.9% in JJA and increase of +3.9 % in DJF) and only 64.4 % in DJF and 62.6 % in JJA of the models coincide in the sign of change. The two mandatory simulations of ACQWA are near the median of the ensemble with respect to precipitation change.

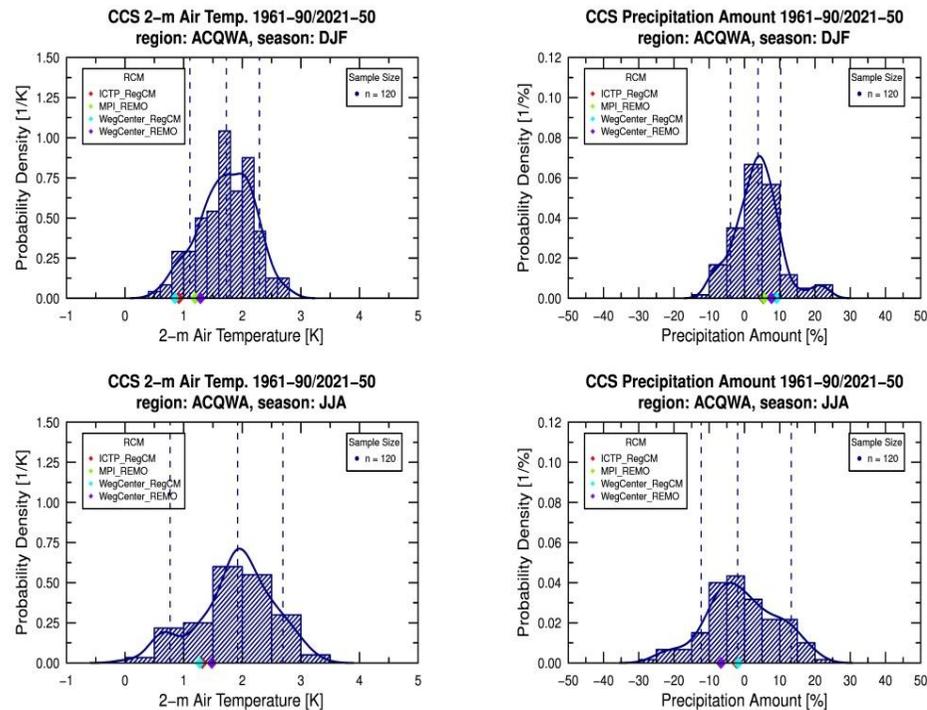


Figure 8. Histograms and kernel density estimates of the reconstructed changes in winter and summer 2-m air temperature (left panels) and precipitation amount (right panels) between 2021-2050 and 1961-1990 in the ACQWA region. Changes of precipitation amount are calculated relative with respect to 1961-1990. The dashed lines represent the 10th-, 50th-, and 90th-percentile.

The variance decomposition of precipitation climate change reveals that the choice of the RCM is by far more important than in the case of 2-m air temperature. Particularly in MAM and JJA the RCM contribution to the total uncertainty is larger than that of the GCMs (not shown).

High resolution scenario simulations with the ICTP regional climate model RegCM3.

Overview: To be able to assess climate change impact on the water cycle, it is essential to bridge the gap between the global climate resolution and the resolution needed for the hydrological model to be able to simulate the impact of climate change on water resources. For this purpose, regional climate models are used to downscale the global climate model output to a higher resolution regional scale. This kind of exercise is not only done for increasing the model output resolution but also to be able to simulate the local climate feedbacks that are relevant for the climate change signal within the alpine region, where the snow albedo feedback is one key process that modulates climate evolution.

Added value from the ACQWA project: In mountain regions where there are river basins with annual cycle discharge mainly driven by snowmelt, the resolution of the climate simulation can be crucial for climate impact studies. To estimate the change in the hydrological annual cycle of such basins, a detailed spatial description is required for snow coverage, precipitation distribution and temperature. By comparing the high resolution (3km) climate simulation completed for the project with a state-of-the-art climate simulation completed for previous studies (25km) it is possible to highlight some important differences. For example we computed the change of dates for the 25th, 50th and 75th percentile of quarterly flow for the two ACQWA basins in the Alps, namely the Po and the Rhone.

What is possible to observe from figures 9-11 is that there are regions of the Po basin where the change of date of the 25th percentile of quarterly flow are very different if looking at the 25km resolution or at the 3km resolution. For example if



panel *a* and *b* of Figure 9 are compared, it is seen that at 25km resolution there are points with positive values of change, so the date of the 25th percentile is moving forward in the year. This is completely different at the 3km resolution where for the same point negative values of -40 days are observed. Large differences are also found for the Rhone basin (panel *c* and *d*). Most of the basin has no signal for the low resolution simulation; the same basin shows a 20-50 days shift towards the beginning of the year, when considering the high resolution plot.

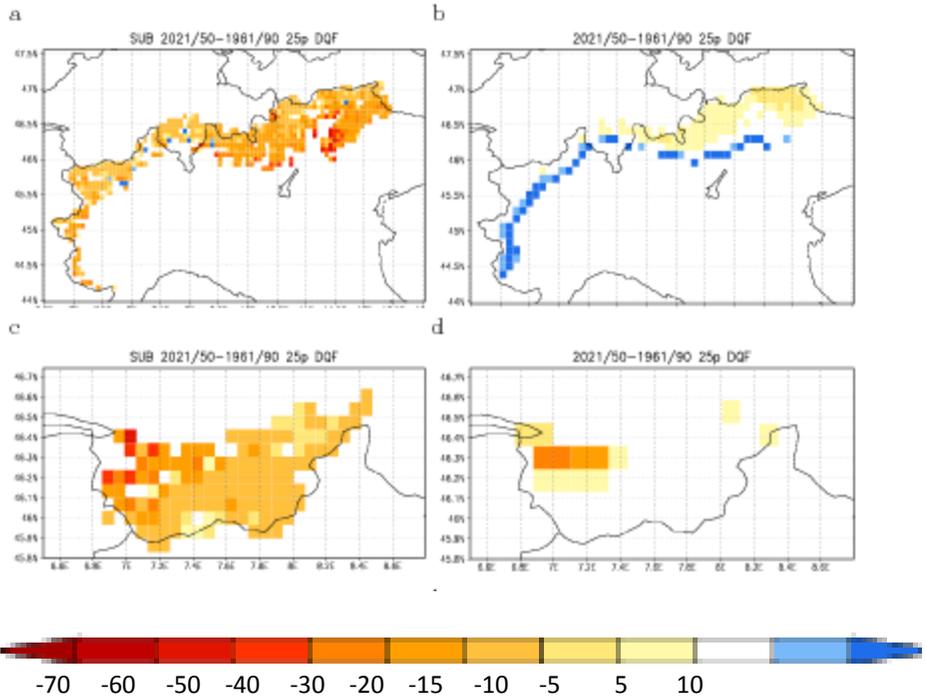


Figure 9: Differences between the future (2012/50) and reference simulations for the 25th percentile date of quarterly flow. Left column is for the 3km resolution, right column is for the 25km resolution. Panels *a* and *b* are for the Po basin and *c* and *d* for the Rhone basin. Units are days.

The same is true for the 50th and 75th percentile plots and the biggest differences are found for the Rhone basin. The high resolution plot for the 75th percentile of the Rhone basin show a negative difference up to one month compare to the present day and this is not shown at all for the low resolution simulation.

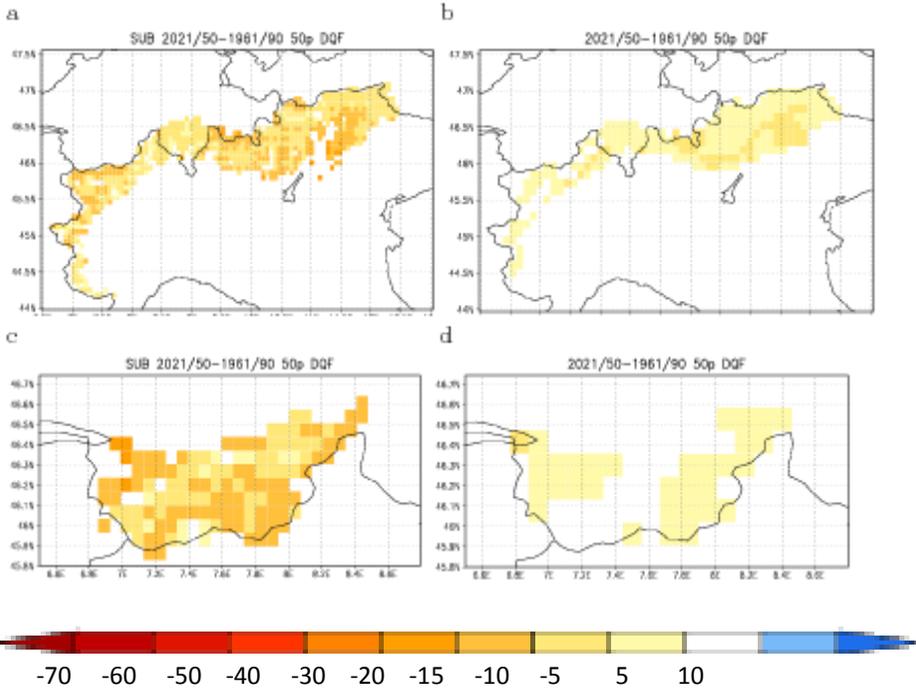


Figure 10: Differences between the future (2012/50) and reference simulations for the 50th percentile date of quarterly flow. Left column is for the 3km resolution, right column is for the 25km resolution. Panels *a* and *b* are for the Po basin and *c* and *d* for the Rhone basin. Units are days.



Policy relevance of this research: These kinds of results need to be taken into account when mitigation policies are to be developed. The shift of the date of quarterly flow of the percentile considered can be quite crucial for all water related activities in a future climate. For example hydropower reservoir management will certainly need to be adapted to take into account the greater availability of water in the earlier months of the year and a longer summer period with much less water left for the runoff. The uncertainty associated with these results is also dependent on the resolution that is used for such simulations.

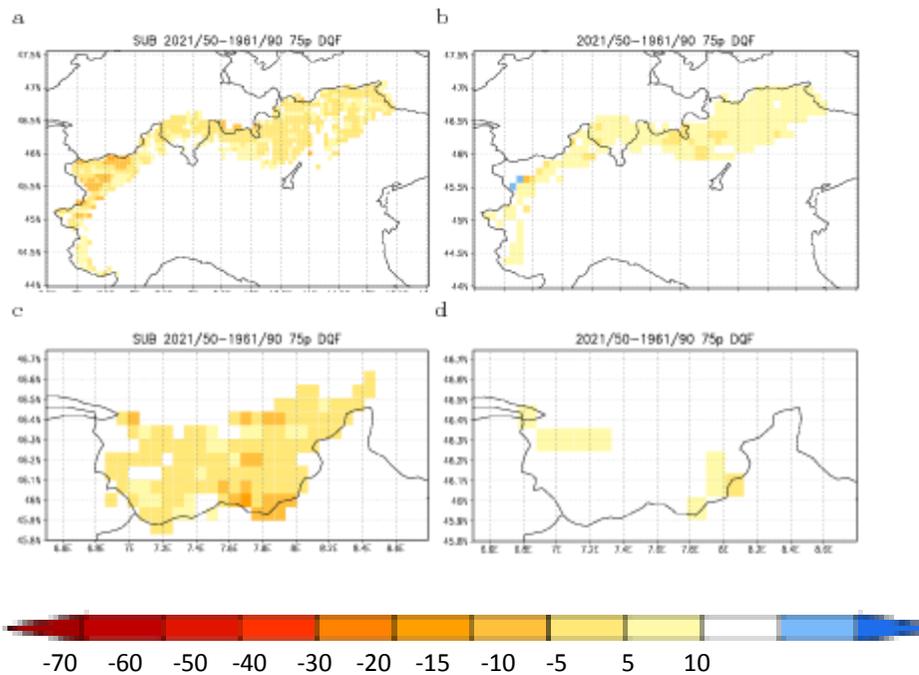
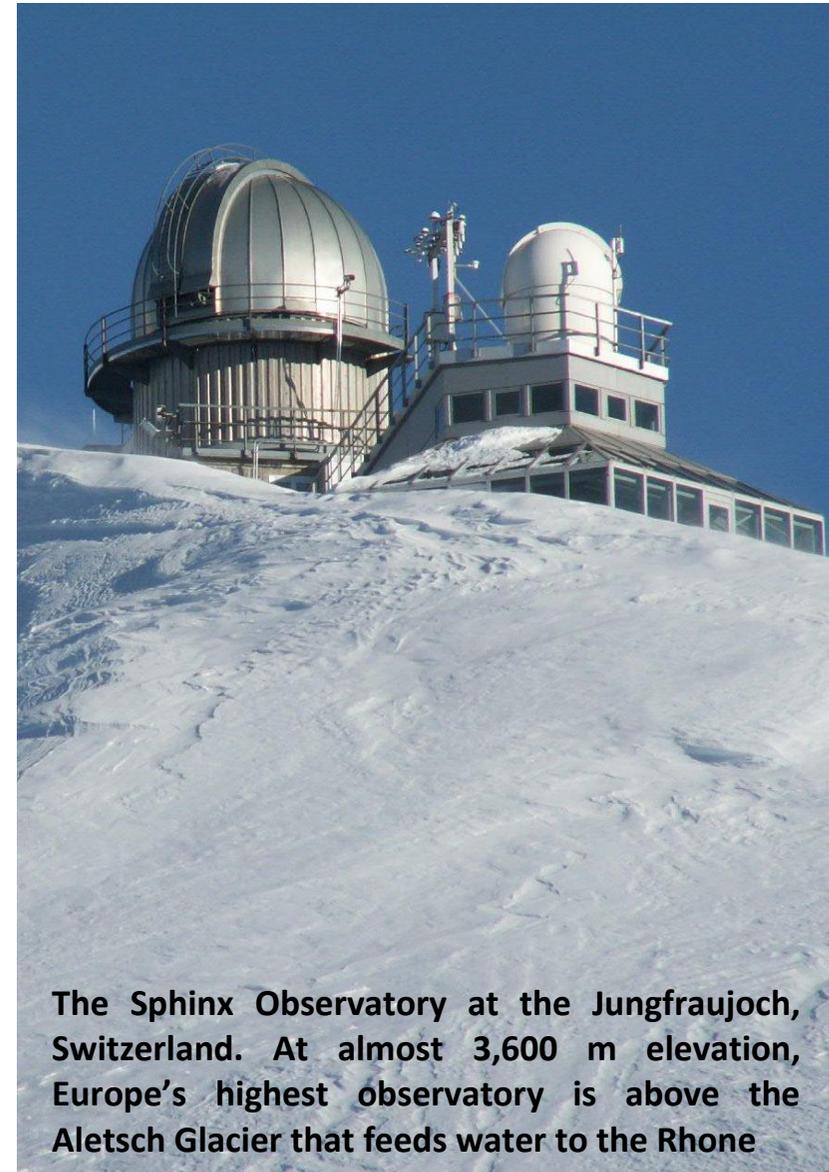


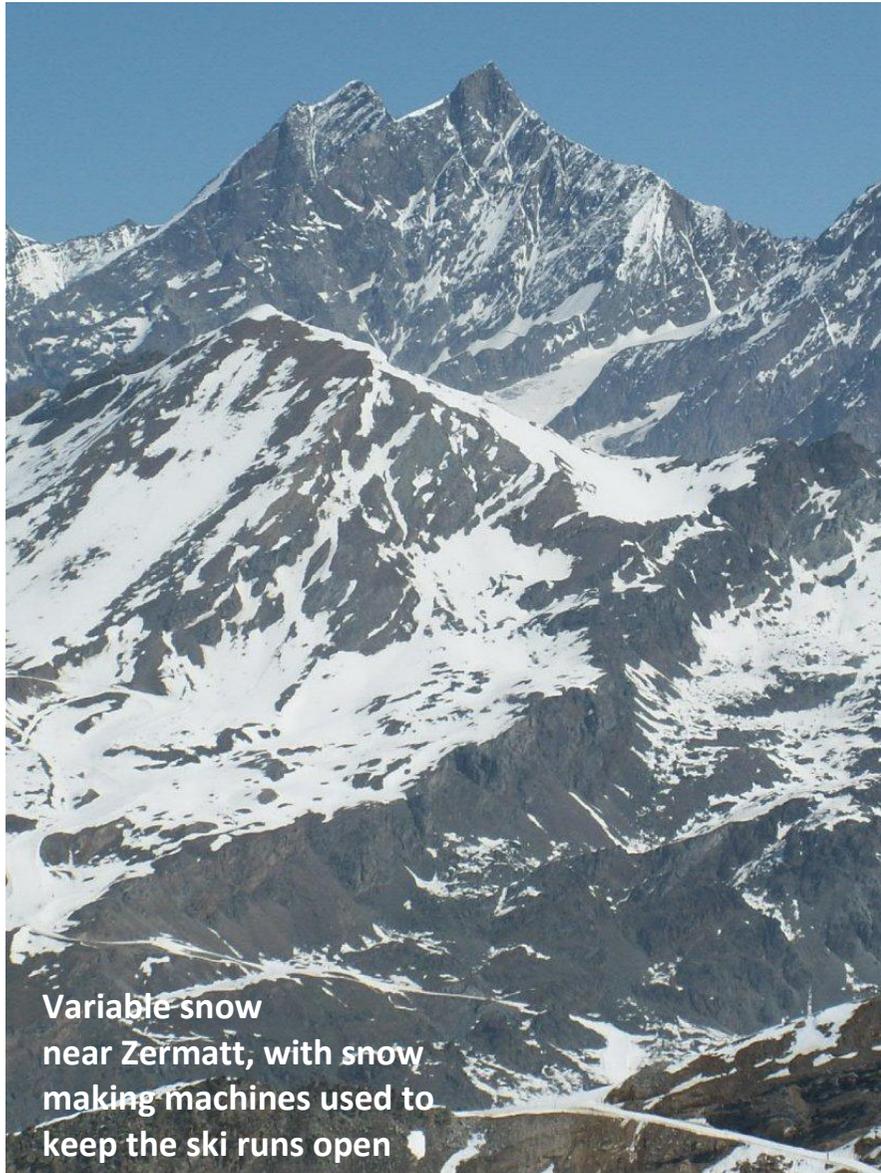
Figure 11: Differences between the future (2012/50) and reference simulations for the 75th percentile date of quarterly flow. Left column is for the 3km resolution, right column is for the 25km resolution. Panels a and b are for the Po basin and c and d for the Rhone basin. Units are days.



The Sphinx Observatory at the Jungfrauoch, Switzerland. At almost 3,600 m elevation, Europe's highest observatory is above the Aletsch Glacier that feeds water to the Rhone



Projected changes: Snow and ice



Variable snow near Zermatt, with snow making machines used to keep the ski runs open

SUMMARY OF KEY FINDINGS

- Alpine snow cover will decline due to temperature increases (more rain/less snow), particularly at mid-latitude locations between 1000-2000m.
- Results from a novel numerical model (includes water flow in a sub-glacial drainage network) projects that climate change will affect the stability of certain alpine glaciers.
- State of the art, continuous mass balance models project a high variability of progressive glacier retreat for 2001-2050 and a related ice volume reduction for 6 contrasting alpine glaciers.
- Debris-free glaciers are projected to have a faster negative mass balance in comparison to those covered by a thick layer of debris. Higher spring and summer melting occurs in 2031-2050.
- Glacier retreat may slow where glaciers become confined to high elevations if accumulated precipitation in winter is high; ice melt contribution to runoff in glacierized catchments accordingly is projected to gradually disappear.



Remote-sensing of changes in snow cover

Overview: Remote sensing provides a unique opportunity to address the question of snow cover regime changes at regional scale. Since the availability of daily optical satellite data at the end of the 1980's (NOAA-AVHRR), methods have been developed to compute changes in snow surface area (SCA) and snow cover duration (SCD). The main parameters analyzed are the timing and duration of the melting season under current and future climate conditions. In this context, a remote sensing database of snow cover dynamics over a time period of 10 hydrological years (2000-2010) was compiled. It focused on the four watersheds of the ACQWA project, namely the upper Rhone (5'300 km²) in Switzerland, the upper Po (37'800 km²) in Italy, the Aconcagua in Chile (5'800 km²) and the Syr Darya source region in Kyrgyzstan (110'000 km²). The satellite data were provided by the MODIS Terra MOD-09 images and the MOD-10 snow products (NSIDC).

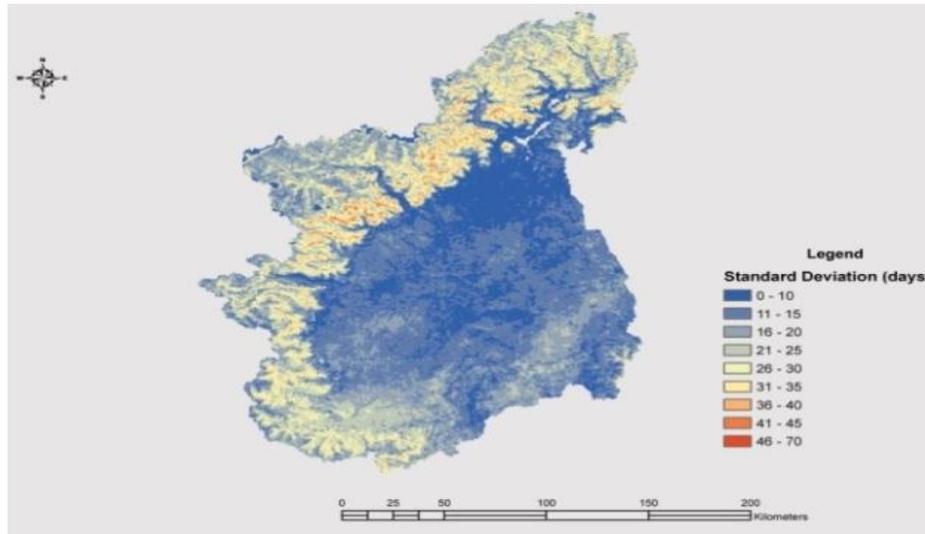


Figure 12: Annual standard deviation of snow cover in the Pô Basin

Added value from the ACQWA project: The results rely on previous studies already conducted in different regions to reconstruct time series of snow cover at regional scale and to analyze snow regime trends under the current climate change context. The specific added values of work within ACQWA include a novel and original method for climate impact detection, as well as scientific results for regions with crucial lack of information (Kyrgyzstan, Chile). Significant progress has been made in using statistical tools to assess the interannual variability of snow cover. Maps of standard deviation highlight sensitive regions where strong temporal and spatial variability becomes a significant proxy of climate change related to recent changes in temperature.

Changes in snow cover in the alpine part of the Rhone catchment

Overview: Numerical simulations to assess the future course of seasonal snow cover under the influence of climate change were performed during the ACQWA project using the detailed snowpack model CROCUS coupled to the land surface model ISBA. In contrast to snowpack components of most land surface schemes within GCMs/RCMs and hydrological models, CROCUS explicitly accounts for internal processes occurring within the snowpack such as compaction, phase change/refreezing and snow metamorphism.

Added value from the ACQWA project: During the ACQWA project, the model was driven by atmospheric fields from the RCM REMO at a horizontal resolution of 10x10 km² and run for a century, from 1950 to 2050. Regardless of the metric used to characterize the time evolution of snow conditions, the main outcome from this study is that the seasonal snow cover in Alpine regions is most likely to decline within the next decades, essentially as a result of increases in temperature. This leads to a shift in the snow/rain partitioning towards relatively more rain and less snow precipitation. Such changes are seen to occur particularly at mid-altitude locations, between 1000 and 2000m, which are most sensitive to air temperature fluctuations around the freezing point. The results obtained using the detailed



snowpack model Crocus are consistent with the conclusions drawn from other impact models that use simpler snow schemes.

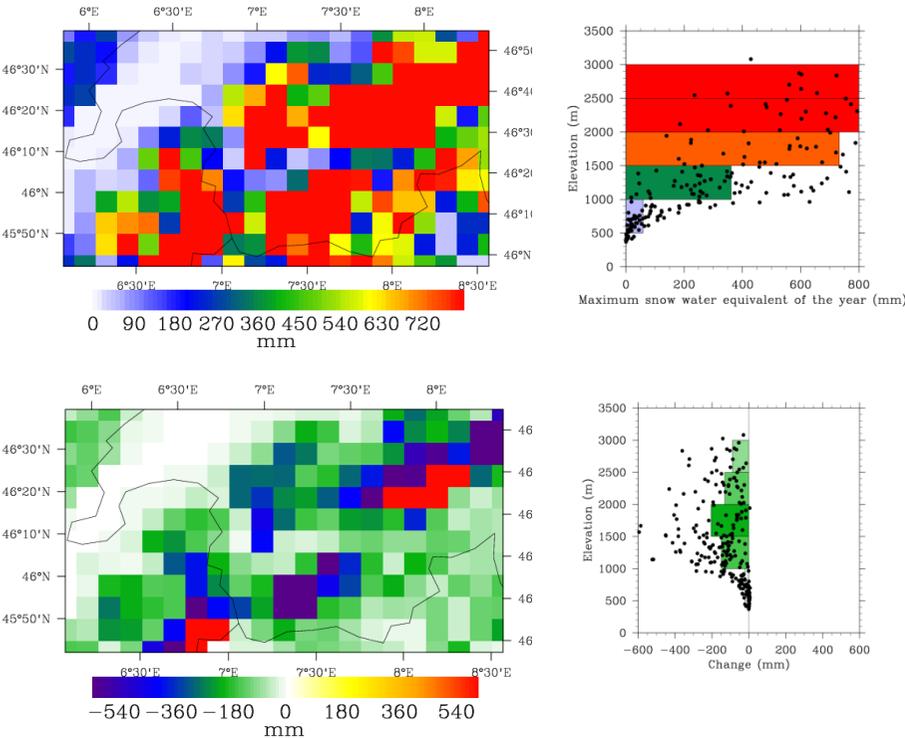


Figure 13: Upper left map mean snow water equivalent (SWE_{max} ; mm); right: altitudinal profile of SWE_{max} for 1950-1969 period. Lower left: map of changes in SWE_{max} changes (mm) between 1950-1969 and 2030-2049; right: changes in altitudinal profiles. Dots in the right-hand figures refer to individual simulation grid points, whose average value over a given altitude band is provided as bars.

Stability of glaciers

Overview: Three different types of instabilities can be identified according to the thermal properties of the interface between the ice and the bedrock. If cold, the maturation of the rupture is associated with changes in surface velocities and the seismic activity generated by the glacier which, if known, can have predictive value. For the other types of instabilities, water plays a key role in the initiation and the development of an instability leading to rupture. If the ice/bed interface is partly temperate, the presence of melt-water at the interface reduces its basal resistance, which enhances the instability but also renders its prediction difficult. The third type of instability concerns steep temperate glacier tongues which experience enhanced basal motion during the summer melt period. Although instabilities of this nature are still difficult to forecast, a novel numerical model that includes water flow in a sub-glacial drainage network has been developed that has predictive capability.

Added value from the ACQWA project: In the context of climate change, the stability of some alpine glaciers may be affected in the near future due to changes in the thermal regime at the ice/bedrock. Although some presently hazardous glaciers may present a lower risk in the near future because of their retreat, some others may evolve towards a critical situation and present a genuine hazard for communities and infrastructure lower down in the valleys. A timely identification of such transitions towards potentially critical hazards is today a challenge that the ACQWA project has contributed to improving.

Policy-relevance of this research: Clearly, studies in the Alps and other glaciated mountains of the world, based on these kinds of analyses, can provide local authorities and regional decision makers with sufficient advance warning to develop and implement precautionary measures to ensure the safety of downslope populations and infrastructure.



The Aletsch Glacier, Switzerland. Summer melt from the largest glacier in the Alps contributes substantial amounts of water to the Rhone River

Glacier response to climatic change

Overview: As outlined by the river basin scale simulations of the Rhone and Po catchments, understanding the glacier response to climate change in mountain regions is extremely relevant for water resources management. Future glacier response is also important to identify the boundary conditions for the evolution of the glacier hazard potential. Climate modifications can indeed influence stream flow regimes, increase downstream landslide and flood risk, and have an impact on hydropower production and other water uses, which strongly depend on melt water. The modelling of glacier response to climate change was carried out at the glacier scale by means of state-of-the-art continuous mass balance models for six different glaciers characterised by different morphological and surface characteristics and representative of the greater Alpine region. The developed and implemented models accounted for, in a spatially distributed fashion and at sub-daily temporal scales, accumulation and ablation processes as well as glacier evolution. The results thus allowed to quantify how glaciers tend to modify in response to changes in climate in order to reach the equilibrium with the current climate. Changes of the mass budget of a glacier and of glacier geometry (surface area, length and volume), were modeled at the highest level of detail in relation to knowledge of glacier behaviour and to the need of long-term modelling under stochastic climate scenario forcing.

The Haut Glacier d'Arolla was used as reference glacier, due to the availability of a large dataset, first to develop and validate the mass balance model and then to run an ensemble of hundred members of future climate predicting changes in of glacier evolution and melt water availability until 2100. On other five glaciers (Aletsch Glacier, Rhone Glacier, Gorner Glacier, Tsa de la Tsa Glacier and Miage Glacier, Figure 14) a reduced set of stochastic scenarios was used to simulate the glacier response expected until 2050.

The predictions of ice volume evolution suggest a progressive glacier retreat for the period 2001-2050 and a related ice volume reduction (Figure 15). However, the heterogeneity of the six study sites, both in terms of glacier morphology, surface conditions and meteorological forcing, indicates that changes are

characterized by different magnitudes. Moreover, the stochastic nature introduced by forcing the mass balance model with an ensemble of localized climate scenarios leads to quite univocal results in terms of ice volume predictions for each single glacier. Regardless of glacier features and future meteorological conditions no stationary ice volume condition is reached throughout the simulated decades. Ablation indeed is generally sufficient to melt the entire amount of snow accumulated during the winter season over the remaining glacierized area and does not lead to changes in the mass balance trend. The six glaciers are therefore characterized by negative mass balance simulated over the next 40 years.

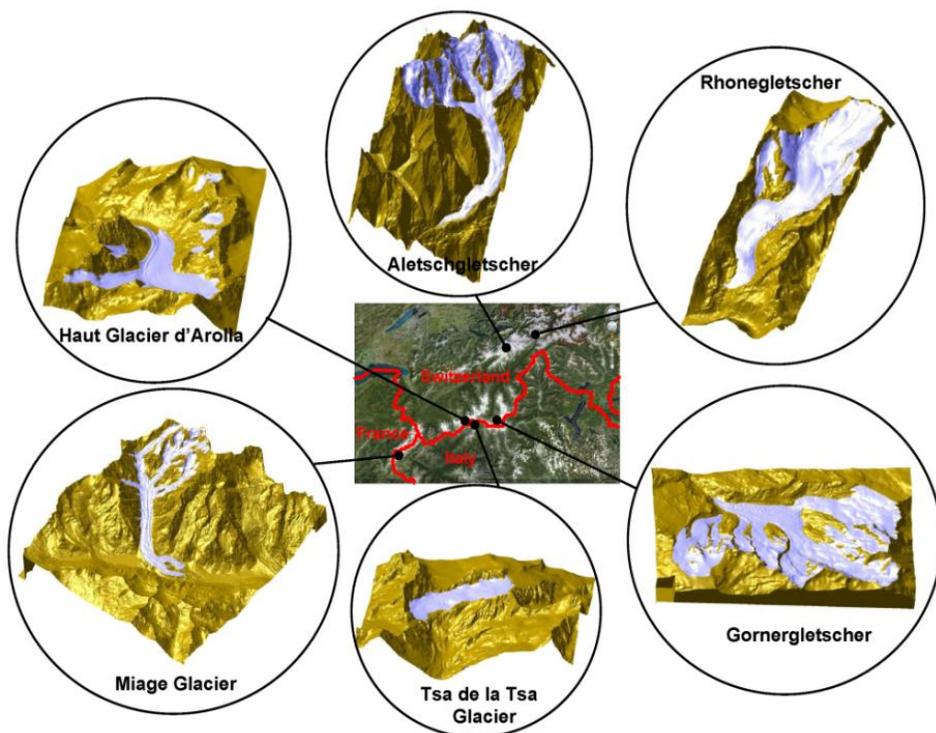


Figure 14: Map of the six Alpine glacier study sites investigated in the ACQWA project.

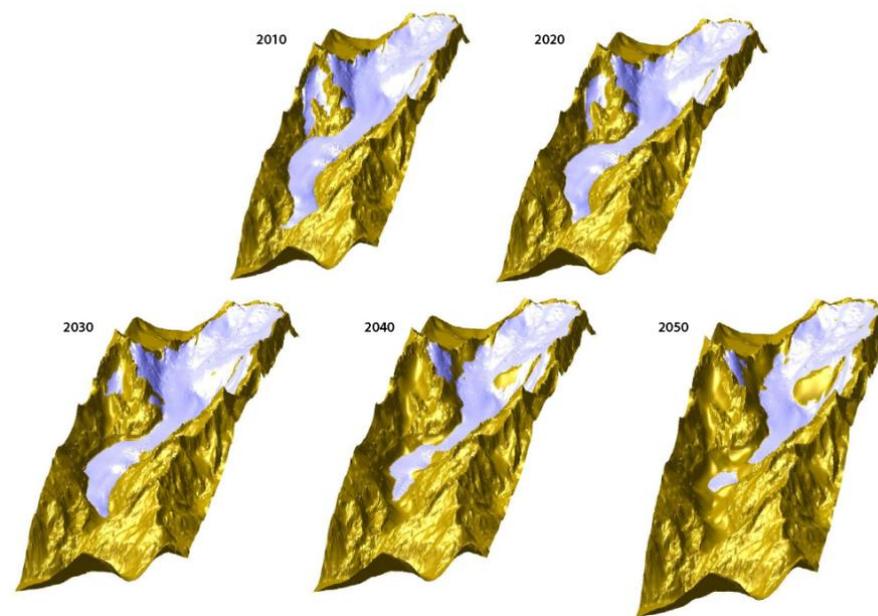


Figure 15: 3-D representation of the extent of the Rhone Glacier and the evolution of related ice volume from 2010 to 2050. These figures are taken from one random simulation.

An interesting result concerns the behaviour of glaciers and/or glacier areas, which are covered by a thick layer of debris. Their response to climate change shows a slower negative mass balance in comparison to debris-free glaciers. The debris cover tends to insulate the ice beneath preserving the same ice. The thin ice thickness located at high elevation and directly in contact with the atmosphere tends to disappear, leading to a scenario in which most of the remaining glacier surface is located at low elevation and is not exposed, but covered by a mantle of rock debris. This result points at the importance of including debris covered areas in realistic simulations of future evolution of glacier, following the pioneering work done within the ACQWA project.

No significant variations in the mean spatial snow melt rates over the simulated decades can be observed. However, the variability introduced by spatial



stochastic climate forcing allows for spatial changes to occur. Some simulations compensated in some decades high snow melt rates at low elevation with low rates at higher elevation or higher snow melt rates were obtained at high elevation, due to future increased temperatures, whereas no snow melt occurred at low elevation, due to the earlier snow disappearance and the higher fraction of liquid precipitation events. Snow melt contribution to the runoff hydrograph, as well as its variability, thus reflect the characteristics of the meteorological forcing, thus indicating the importance of accounting for climate scenarios that are localized, spatially variable and highly resolved in time.

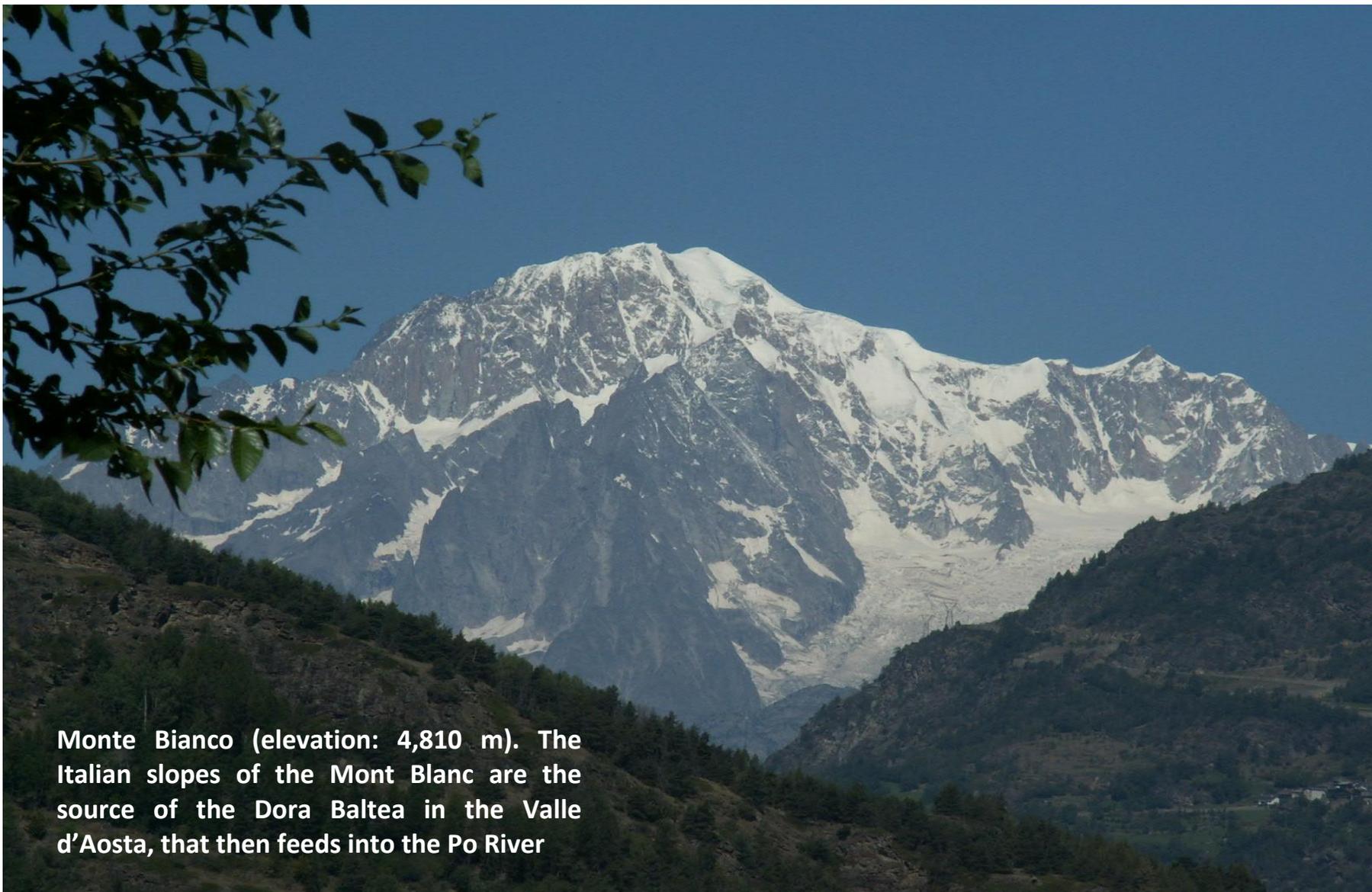
A progressive shift and change in shape of the ice melt rate frequency distribution can be identified across all melting seasons. This is due to new melt events during times of the day that in the current and past climate did not lead, generally, to melt. Thus, anticipated ice exposure in spring generates low melt rates, as temperature is not high enough to cause higher melt rate. In summer more frequent melt occurrence at night is due to higher night temperatures or when the solar radiation contribution is still low, early morning and late afternoon. Low melt increase is also observed in autumn in some decades and can likely be associated to melt at night. Higher frequency of high ice melt rates was also observed in the last two decades investigated (2031 to 2050) both in spring and summer, due to significantly higher temperature and reduced elevation range of the reduced area of glacier cover. In general, the overall ice melt rate is more variable than snow melt due to the transition of most of the investigated glaciers to small scale glaciers. In this respect the timing of the transition and, more generally the impact of climate forcing, is significantly influenced by the glacier morphology, the initial ice thickness distributed over a large elevation range and by the intensity of the local climate change signal, which can be different from the large scale patterns simulated by GCMs and RCMs. The ice melt contribution to runoff in glacierized catchments tends accordingly to disappear gradually. An exception is represented by the Aletsch Glacier, where no large changes for the simulated decades (2001 to 2050) are observed in the ice melt hydrograph.

The gradual disappearance induced by climate change may confine glaciers to higher elevations causing a possible reduction of the speed of glacier retreat. A key

role in this respect is played by the winter accumulated precipitation, which can mitigate (high accumulation) or enhance (low accumulation) the glacier retreat and the backward shift of the accumulation area.

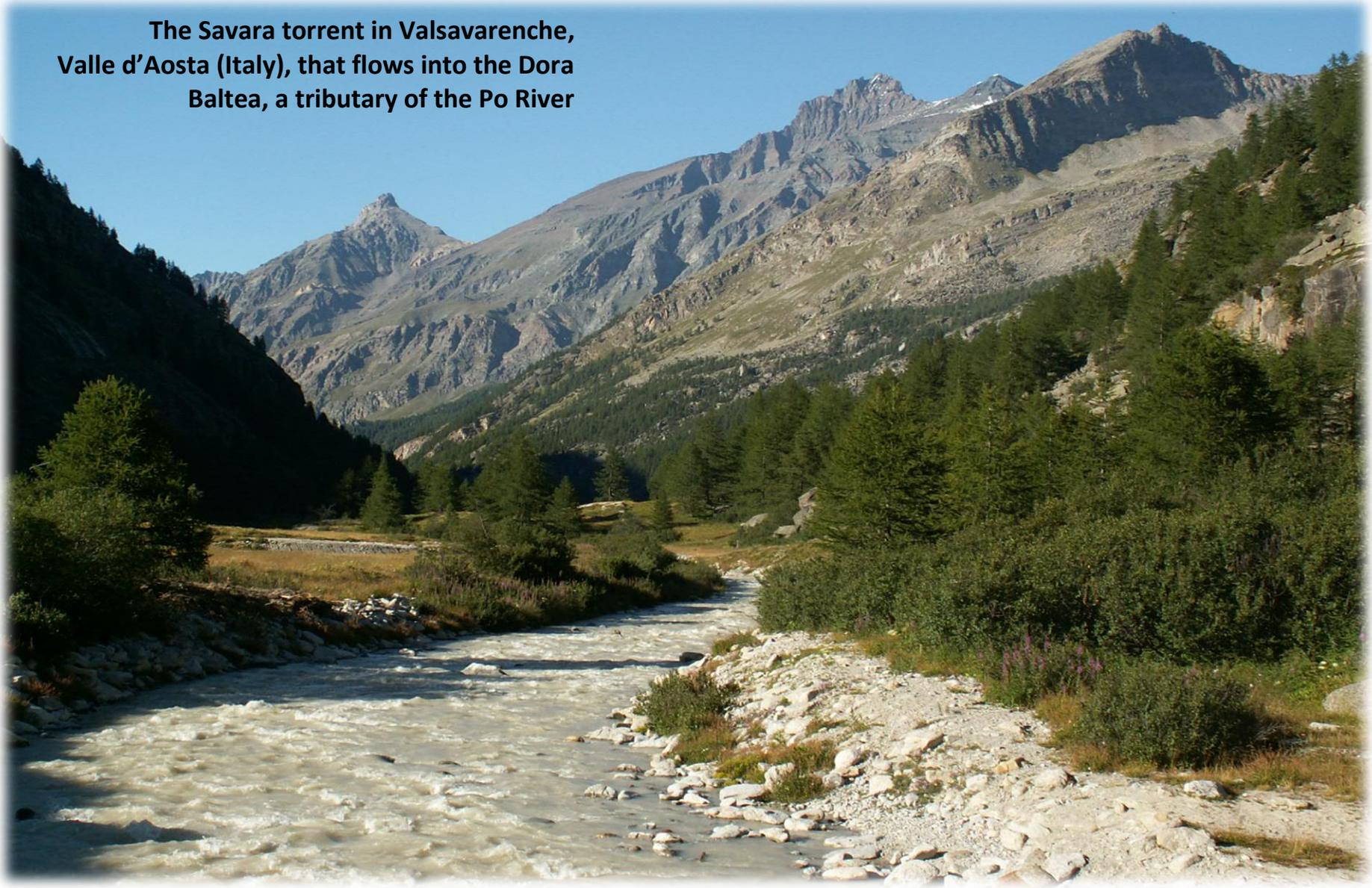
Added value from the ACQWA project: The modelling techniques developed and used in the ACQWA project represent a step forward with respect to existing literature as they allowed to point at some important aspects of the impact of climate change on future glacier evolution. The key elements of the added value are: (i) the identification of the important role played by distributed in space and highly resolved in time localized scenarios, which explicitly model the internal variability of future climate, in modulating the glacier evolution trajectory jointly with the influence of glacier morphology, altitudinal range and ice thickness; (ii) a quantification of the evolution trajectories of different representative glaciers by means of statistical descriptors of ice- and snow-melt changes following ensemble based simulations by means of advanced mass balance glacier models; (iii) a decomposition of the mechanisms by which glacierized catchments will change their runoff regime, also showing relative changes of the runoff components and how these depend on the local climate and the glacier configuration (size, aspect, shape, etc.); (iv) the quantification of the role of debris cover in modifying the glacier retreat pattern in space and time, thus highlighting the importance of including this component in glacier evolution assessments for more realistic predictions.

Policy-relevance of this research: The key message relevant for policy is that climate driven glacier evolution and the related changes in the runoff regime are a highly complex and non-unique-trajectory process. For this reason, the prediction of climate change impacts require to model the forcing with a high level of spatial and temporal detail as well as to adopt modelling techniques that allow to consider all the relevant processes. This might suggest that many of the predictions of glacier evolution available in the literature need to be reconsidered, not so much in relation to the large scale trend signal, but more in relation to the variability that might characterize the change and the consequences for the management of hydropower plants, which depends primarily on snow- and ice-melt of glaciers.



Monte Bianco (elevation: 4,810 m). The Italian slopes of the Mont Blanc are the source of the Dora Baltea in the Valle d'Aosta, that then feeds into the Po River

**The Savara torrent in Valsavarenche,
Valle d'Aosta (Italy), that flows into the Dora
Baltea, a tributary of the Po River**



Projected changes: Hydrology

SUMMARY OF KEY FINDINGS

- The effects of climate change on the hydrological cycle appear less evident in the higher part of the alpine region (e.g. for the high part of the Rhone) than for lower elevations (e.g. Padan Plain, Po).
- RCMs projected impacts of climate change on flow duration curves of mountain tributaries for the Po River exhibit a general decrease of discharge for high durations (low flows) and an increase in discharge for low durations (high flows). Results from GCMs are more variable. Decrease of flow discharge is estimated to be more than 50% of the seasonal average for a large portion of the drainage network.
- Downscaling from 25km to 3km resolution has significant impacts on the change in the annual hydrological cycle due to the detailed spatial description required for snow coverage, precipitation distribution and temperature in alpine regions.
- In the Rhone, internal (stochastic) climate variability is a fundamental source of uncertainty, larger than the projected climate change signal while changes in the natural hydrological regime imposed by the existing hydraulic infrastructure are larger than climate change signals expected by 2050.
- Climate change impacts on stream flow are elevation dependant, with a severe reduction at high elevations due to the missing contribution of water from ice melt and a dampened effect downstream: decrease of water availability in summer and in increase of discharge in winter.
- While local changes may be of some relevance, it is unlikely that major changes in total runoff for the entire upper Rhone basin will occur in the decades up to 2050.



Soil-moisture dynamics using remote-sensing information

Prediction of the future effects of climate change on water availability requires an understanding of how precipitation and evapotranspiration rates will respond to changes in atmospheric forcing. The lack of meteorological forcing at high resolution in time and space, that is required to model hydrological processes in mountain river basins, and the necessity to reduce computational costs in order to perform long time analysis, imply the use of simplified hydrological models.

The FEST-EWB model, a fully physically based hydrological model that computes actual evapotranspiration by solving energy and water balance, was validated against measurements acquired at eddy-covariance stations. The FEST-EWB model was used to assess the accuracy of FEST-WB, a parsimonious version of the hydrological model that was specifically developed for the analysis of the impacts of climate change on hydrological processes in alpine environments. The results show that parsimonious models are accurate enough to capture main processes of hydrological

Distributed basin-scale responses to climate scenarios (Po Basin)

The most common approach to assess the hydrologic impacts of global climate change involves the use of climate models to simulate climatic effects of increasing atmospheric concentrations of greenhouse gases, and hydrological models to simulate water-related impacts of climate change. River discharges and their temporal distributions are strongly affected by high mountain areas that are particularly sensitive to global warming. Therefore the quality of hydrological impact investigations, even for larger catchments, depends on the capability to model those specific processes in mountains.

Comparison of parsimonious and fully physically based models showed that simpler models, despite their approach for computing evapotranspiration based only on temperature, are sufficiently robust and accurate to perform hydrological

impact investigations of climate change for alpine river basins investigated in the ACQWA project. The bias resulting from the approximation of the method implemented to compute evapotranspiration is lower than uncertainty associated with different climate models, however.

Impacts of climate change on hydrological processes were assessed by comparing hydrological model results for the upper Po river basin driven by two different regional climate models (REMO and RegCM3) for the decade 2041-2050 with respect to the decade 2001-2010. Increase of temperature ranges between 15.2 and 17.5%, while variation of mean annual precipitation ranges from 1.1 to 9.6 %.

Precipitation increase is mainly concentrated in the period from January through March, and causes an increase of snow water equivalent during this period, followed by an accelerated melting period in the mountains. The rise in temperature causes an increase of actual evapotranspiration, mainly in the summer period that counteracts the influence of the larger amounts of summer precipitation on river discharge. Impacts of climate change on flow duration curves of mountain tributaries of the Po River, as provided by different regional models, exhibit a general decrease of discharge for high durations (low flows) and an increase in discharge for low durations (high flows). The two climate models yield different results for the impact on flow duration curves in Po the Po river basin. In particular, the REMO model data results in an increase in discharge for both low and high durations, while use of the RegCM model data yields a decrease in discharge for both low and high durations except for the period ranging from 12 to 58 days.





Distributed basin-scale responses to climate scenarios (Rhône)

Overview: The physically based distributed modelling methodology, as one approach to assessing changes in hydrology, allowed to model the response of the (upper) Rhône river to a high number of stochastically downscaled ensemble members at hourly temporal resolution and with a spatial discretization of 250x250 m, also keeping the highest detail of representation of anthropogenic disturbances, such as hydropower, water abstraction and irrigation. This level of detail is unprecedented, particularly for studies in Alpine regions, and represents a new basis, as compared to existing studies, for investigating options for adaptation policies. The results show how climate change effects on stream flow propagate from high elevation headwater catchments to the river in the major valley, highlighting the damping effect of the river network on the mean and on the extremes, even when the latter show large increases in the upper river reaches. The simulations also indicate that changes in the natural hydrological regime imposed by the existing hydraulic infrastructure are likely larger than climate change signals expected by the middle of the 21st century in most of the river network. Results suggest that internal (stochastic) climate variability is a fundamental source of uncertainty, typically larger than the projected climate change signal. Therefore, climate change effects in stream flow mean, frequency and seasonality are masked by possible natural climatic fluctuations in large part of the analyzed regions. Simulations also identify regions where strong precipitation increase in the February to April period leads to flow larger than natural climate variability during the melting season. Despite the strong uncertainties induced by stochastic climate variability, an elevation dependence of climate change impacts on stream flow could be identified, with a severe reduction due to the missing contribution of water from ice melt at high-elevation and a damped effect downstream. The presence of reservoirs and river diversions tends to decrease the uncertainty in future stream-flow predictions that are conversely very large for highly glacierized catchments. Despite uncertainty, reduced ice cover and ice melt are likely to have significant implication for aquatic biodiversity and hydropower production. A decrease of

August-September discharge and an increase of hourly-daily maximum flows appear as the most robust projected changes for the different parts of the Rhône catchment. This will have a significant impact on hydropower production and management. Water abstraction and irrigation needs, as described by the available data, will likely be marginally affected, as they represent a very small fraction of the use of the available water resources. However, while local changes may be of some relevance, it is unlikely that major changes in total runoff for the entire upper Rhône basin will occur in the decades up to 2050.

Added value from the ACQWA project: Two areas providing added value include firstly the evidence of the importance of detailed simulations that account for the interaction between the effects of climate change and anthropogenic controls at a high space and time resolution; and secondly the extreme importance of including internal climate variability in climate change analyses, especially when compared to the limited uncertainty accounted for by deterministic projections. Because of its detailed space-time nature, the methodology adopted to simulate the impact on the hydrologic regime of the Rhône and Po catchments allowed to investigate the propagation of the impacts throughout catchments of increasing size and along the entire river network, thus quantifying the magnitude of impacts on water resources depending on the location in the catchment and especially their differences. Accordingly the results could be useful both to identify the needs for further refinement of the methodological approaches, and to guide more specific impact studies.

Policy-relevance of this research: The policy relevance basin response simulations is twofold. On the one hand, the study showed clearly the importance of modelling the small scale variability of both climate forcing and basin response, which is consistent with the scale of water resources management, and the relevance of considering the interaction between anthropogenic controls and climate change in heavily managed water resources systems such as those, where diffused impounding leads to an almost artificial stream flow regime across the entire basin. On the other hand, the study

suggests that adaptation measures or management decisions may require, in some cases and in addition to impact analyses, studies that are based on reliability and vulnerability criteria, as recently suggested by other studies, rather than on extremely uncertain scenarios. This is of particular importance for planning horizon over which the magnitude of the change is comparable, if not smaller, than the intrinsic natural variability of climate.

Shifts in hydrology in the Po, Rhone and Kyrgyz catchments using the CHyM hydrological model

Overview: The effects of predicted climate changes on Hydrological cycle of Po and Rhone catchments have been studied by forcing the CHyM hydrological distributed model with 8 different climate scenarios simulated by RegCM and REMO regional climate models. A further simulation with the RegCM model has also been used to simulate the future hydrological scenario on the Kyrgyzstan catchments. The future discharge trend has been analyzed for the whole drainage network, obtaining a map of such effects for different seasons.

Added value from the ACQWA project: Downscaling of climatic scenario at hydrological scale can be considered an important challenge after the downscaling from GCMs to RCMs models. The results are summarized as follows:

- The simulated effects of climate change on the hydrological cycle appear to be considerably different for Po and Rhone basins and also for different regions within the same basin. The same conclusions can be reached using the 8 different simulated climatic scenarios;
- The decrease of water resources is shown to be more critical for the entire flood plain during the fall season, leading to a loss of 200 m³/sec in the Po outlet point. The decrease of flow discharge is estimated to be more than 50% of the seasonal average for a large portion of the drainage network;

- The effects of climate change on the hydrological cycle appear less evident in the high part of the Rhone valley and, more generally, in the higher part of the Alpine region. The situation is quite different for Kyrgyzstan, where, for a large portion of simulated domain, increases in discharge during winter months and decreases of water availability during summer are observed.

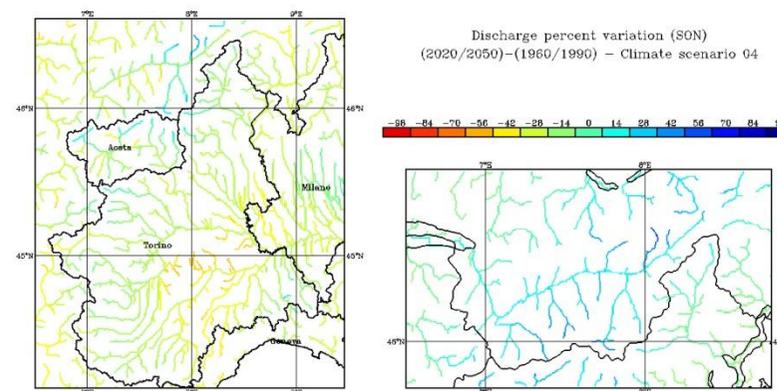


Figure 16. 30-year mean discharge difference (percentage) in the Po basin (left panel) and Rhone basin (right panel).

Policy-relevance of this research: The effects of climatic change on the hydrological cycle are shown to be considerably different for different basins; these changes show sharp contrasts for different seasons. These conclusions lead to the need of specific studies aiming to assess the actual impact of climate changes for specific basins. Another specific analysis has been carried out by the CHyM model, in order to assess a possible increase of flood occurrence in the future years. This has been done using specific tools embedded in the CHyM model allowing to predict the possible alert situations in the simulated domain. This research represents one of the first attempts to estimate the amount of such increase as the geographical distribution of expected floods.



Extreme events and climate-driven hazards

SUMMARY OF KEY FINDINGS

- A novel algorithm based on multivariate extreme value theory has been applied. This type of mathematical instrument provides a relevant general statistical framework to model the frequency and distributions of rare weather events.
- Investigations suggest a remarkable intensification of extreme precipitation events at the end of the 21st Century in Switzerland; increase in intensity and frequency in the upper and southern Rhone valley have already been observed since 1990.
- Cut-off low systems are significant contributors (20% - 95%) to large scale heavy precipitation events in the most exposed northern and eastern parts of the Alps; current models underestimate the precipitation in regions where an essential part of the precipitation stems from cut-off lows.
- Global seasonal precipitation extremes for the 21st Century (using 8 new high- resolution GCM simulations) show that in the mid and high latitudes of both hemispheres, a significant intensification of extremes is evident in all seasons by the end of the century.
- Despite uncertainties, recent developments at high-elevation sites clearly show that the sensitivity of mountain and hillslope systems to climate change is likely to be acute, and that events beyond historical experience will continue to occur as climate change progresses.
- Glacier down-wasting and the related formation of ice-marginal lakes, ice avalanches and debuttrussing is leading to rockfalls and slope instability at progressively higher elevations; volume, but not frequency, of debris flows is likely to increase further.



Advanced statistics for extreme climate analyses

Overview: Within the ACQWA project, novel statistical methods were proposed to analyze extreme events, to develop new algorithms to implement such methods and to apply those approaches to hydrological and climate data. Among many byproducts of this project, three specific topics are highlighted here: spatial clustering of weekly maxima of hourly French rainfall, non-stationary analysis of heavy precipitation in Switzerland, and the study of global changes in seasonal extreme precipitation. For the first topic, one of the main objectives of statistical climatology is to extract relevant information hidden in complex spatial-temporal climatological datasets. To identify spatial patterns, the most well-known statistical techniques are based on the concept of intra and inter clusters variances (like the k-means algorithm or EOF's). As analyzing quantitatively extremes like heavy rainfall has become more and more prevalent for climatologists and hydrologists during the last decades, finding spatial patterns, simple and fast clustering tools tailored for extremes have been lacking. In this context, a novel algorithm based on multivariate extreme value theory was proposed. Comparing with classical clustering on weekly maxima of hourly precipitation recorded in France (Fall season, 92 stations, 1993-2011) shows that other patterns, specific to extremes events, were missing when employing traditional approaches.

The second example dealt with the inference of high rainfall return levels in a situation of non-stationarity in space and time. A new estimation technique of such high return levels based on semi-parametric approaches within the mathematical framework of Extreme Value Analysis has been implemented. A set of roughly 400 daily precipitation series covering the entire Switzerland has been collected and come from the data archive of MeteoSwiss.

The third example focuses on exploring how anthropogenically warmed climate is expected to sustain a larger increase of precipitation extremes. Here, new evidence is provided on global seasonal precipitation extremes for the 21st

century, using 8 new high-resolution global climate Model simulations. In the mid and high latitudes of both hemispheres, a significant intensification of extremes is evident in all seasons at the end of the century. In the subtropics/tropics models provide different responses and often a reliable description of extremes cannot be achieved.

Added value from the ACQWA project: Climate/weather extreme events seriously affect population and economies. The understanding of their behavior is, therefore, crucial. Extreme Value theory provides an ideal framework to carry out such analyses. For this package focusing on analyzing extreme events, ACQWA has aimed at providing relevant general statistical tools to model the frequency and distributions of rare events, such as heavy rainfall or intense droughts. The mathematical instruments developed in this framework are universal in the sense that they could be used for other disciplines, e.g., insurance and finance. The open statistical packages developed offer a free and flexible platform to analyze extreme events in space, time or in a non-stationary context. Consequently, this openness and generality brings a significant added value from the ACQWA project.

Policy-relevance of this research: In terms of policy-relevance, the algorithms could be used to help policy makers who are in charge of flood planning, insurance or other extreme events related fields. In addition, these probabilistic methods could be implemented in detection and attribution of extreme events, which is an important issue for decision making when exploring climatic scenarios and impact studies over future decades.

Cut-off low systems: Extreme precipitation as a major contributor to annual rainfall

Overview: Cut-off low systems are significant contributors to large scale heavy precipitation events in the Alpine region. Their total contribution ranges between 20 % - 95 %, essentially in the most exposed northern and eastern parts of the Alps. Using new numerical algorithms, it has been possible to establish a detailed climatology of these phenomena for Europe for the period 1971-1999, and to investigate the links between cut-off lows and Alpine-scale precipitation. Unfortunately, current regional climate models have limited capability for simulating such events, implying that model simulations underestimate to a large degree the amounts of precipitation in regions where an essential part of the precipitation stems from cut-off lows.

Added value from the ACQWA project: This part of the ACQWA project has enabled new information to emerge in comparison to earlier investigations. Indeed, the study on cutoff lows has enabled to identify not only the type of weather elements that need improved representation in climate models, but has also quantified for the first time the fraction that cut-off lows contribute to overall precipitation in regions most subject to these extreme events.

Extreme daily precipitation: application of theoretical approaches

Overview: Weather and climate extremes affect societies and ecosystems and sometimes induce fatalities and large financial losses. To reduce the impact of such events and to improve risk assessment studies, it is essential to obtain accurate statistical features of extremes. In the framework of the Extreme Value Theory, a new method has been established, based on Generalised Probability Weighted Moments and Kernel regression.

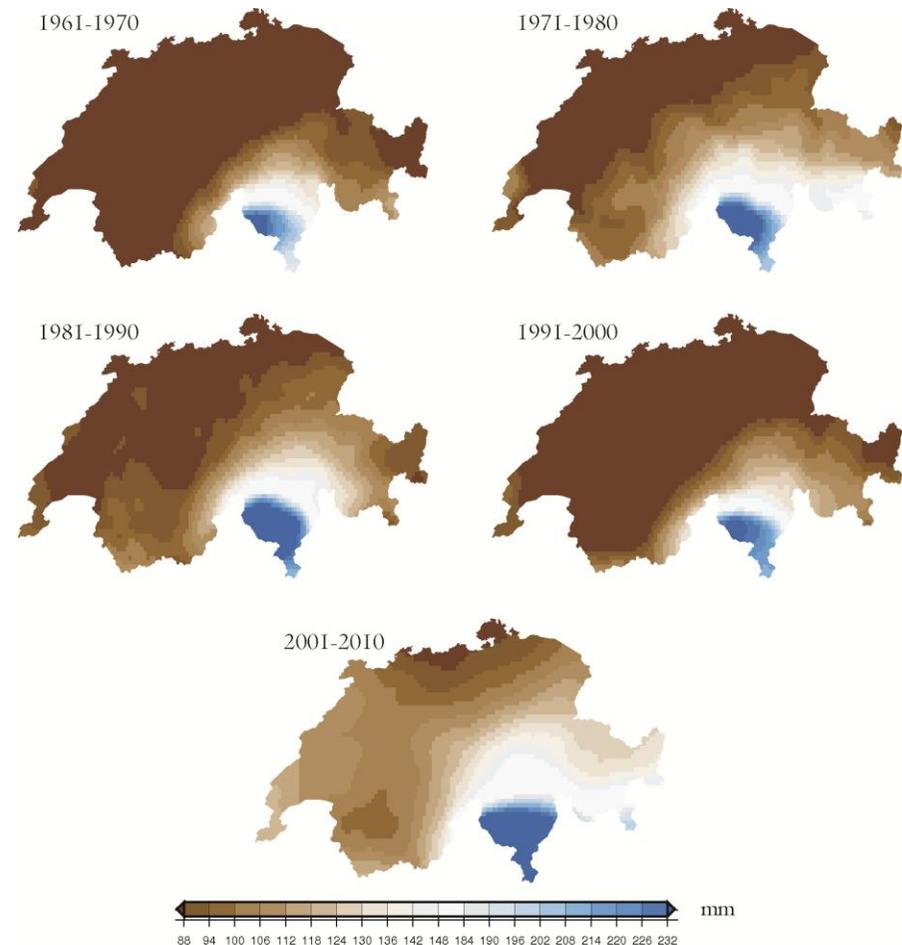


Figure 17. 50-year return levels of precipitation (mm) for Switzerland, 1961-2010. Spatial-temporal differences are evident with the north-south gradient and the tendency towards higher return levels in the 1980s as well as the recent decade over the Upper Rhone valley.



The method provides an accurate estimation of heavy, extreme daily precipitation by statistically modeling exceedances above a high threshold and handling for spatio-temporal non-stationarities. The method is fast (no optimization is required) and flexible (non-parametric) and can be applied to large data sets from catchment area series to global climate models. Importantly, the method is computationally inexpensive.

A similar approach has been applied to high resolution CMIP5 Global Climate Models. Results show a remarkable intensification of extreme precipitation events at the end of the 21st century (especially under the RCP8.5 scenario) in all seasons. A parallelized R package of the method has been developed and is available for use by hydrologists, climatologists, engineers.

Added value from the ACQWA project: This part of research of the ACQWA project has enabled the development of a state-of-the-art fast and flexible methodology that takes into account spatio-temporal non-stationarities in the statistical modeling of the daily precipitation exceedances distribution. The method can be also applied to large data sets. The new methodology allows in a computationally inexpensive approach to accurately characterize the statistical features of extreme precipitations, like return values (Figure 17).

Warm spells in the Rhone valley

Overview: In order to achieve a better understanding of the potential impacts of climate and climate change over the target areas, temperature extremes carefully and accurately studied. Here and for the first time, warm spells both in winter and summer were identified and analyzed for the last six decades (1951-2009) over the Upper and Southern Rhone valley by applying a recently developed approach. The approach is based on the identification of consecutive sequences of days (with a certain tolerance) with daily maximum temperature above a station-specified threshold. An increase in the intensity and frequency seems to have affected the two areas in the last 30 years in both seasons,

especially after 1990. Furthermore, the higher intensity of the warm summer spell in the Southern Rhone valley, especially at the end of the period, can be highlighted. Finally, the 1983, 2003 and 2006 summer events are clearly visible in both valleys.

Added value from the ACQWA project: The application of the state-of-the-art methods to recently released data sets gave the possibility to identify, estimate and analyze for the first time warm spells over the target areas both for winter and summer. The approach can be easily adapted for other regions of the world and it is available to the climate community.

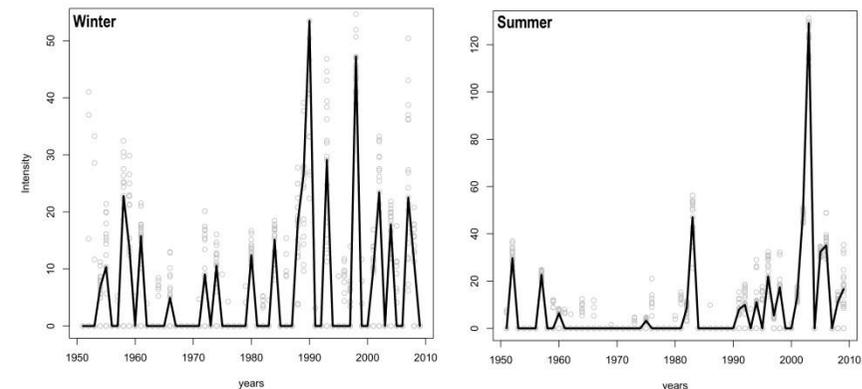


Figure 18. Intensity of winter and summer warm spells from 1951-2009 in the Upper Rhone Valley. Grey dots are associated with values of intensity calculated for each grid point. The black solid line represents the median of the values.



Hydrologically-relevant geomorphologic hazards

Overview: This component of the ACQWA project consisted in addressing the impact of climate change on hydrologically-relevant geomorphologic hazards consisted in the development of (i) the slope stability component of the distributed hydrological model used for climate change impact analysis and (ii) an advanced slope stability model, which can simulate the effect of climate change on the occurrences of shallow landslides at high resolution in time and space.

The soil slip simulation tool that was implemented in the distributed hydrological model during this study is based on the concept of the infinite slope model. This model is aimed at exploring the ability to reproduce the slope response using a coarse terrain resolution at large catchment scales (river basin mesoscale, of the order of hundreds of km²) and thus for large scale simulations that are aimed at predicting hazard changes at the regional scale.

The second model was developed to investigate more in detail and at finer spatial scales the stability of slopes and their dependence on the detailed description of the involved hydrological and geotechnical processes. The HYDROlisthis model is aimed at fine spatial scale resolution (of the order of the meter) and thus suitable for local scale (i.e., hill-slope and catchment scales of the order of 10 km² at most) investigations of slope stability response to climate change forcings. The model consists of an hydrological and a geotechnical component, which are coupled together. The hydrological component takes into account the 3D variably saturated flow through soil, surface runoff, and hysteresis of the Soil Water Retention Curve (SWRC), topography-dependent solar radiation, potential evapotranspiration and root water uptake. The geotechnical component, which is based on a multidimensional limit equilibrium analysis, considers simple earth pressure conditions acting on the lateral sides of the soil column. These forces are computed using the coefficients of active, passive and at rest pressure, which are computed taking into account unsaturated conditions.

Both models showed, when applied to case studies, to be able to capture the observed slope instabilities at the scale for which they were developed. In particular, they showed significantly-better performance than statistical models, especially because they explicitly account for the spatial and temporal variability of the soil water dynamics, which is a key variable in the triggering of shallow landslides. This result is particularly valuable in the context of analyzing the shallow landslide hazard potential due to climate change, as they can explicitly account not only for the changes of the climatic forcing, but also for the consequences that this can have on the soil water dynamics and the related soil-vegetation medium response.

Added value from the ACQWA project: The two slope stability models developed within the ACQWA project have contributed to the development of novel science for the simulation of shallow landslides hazard risk. The successful test of their performance at the respective scale of use and their computational efficiency points at their suitability for future analyses driven by stochastic downscaled scenarios to assess changes of hazard potential in a probabilistic fashion from MonteCarlo simulations.

Policy-relevance of this research: The successful tests and the computational efficiency of the developed models suggest that detailed impact assessments based on physically based and highly specialised models are possible and should be used for those areas, where shallow landslide hazards are expected, on the basis of preliminary and highly simplified and/or conceptual simulations, to be modified by climate change.

Natural hazards

Overview: Changes in temperature and precipitation are likely to have a range of secondary effects on the occurrence of natural hazards, in particular also in mountain environments. However, while theoretical understanding exists for

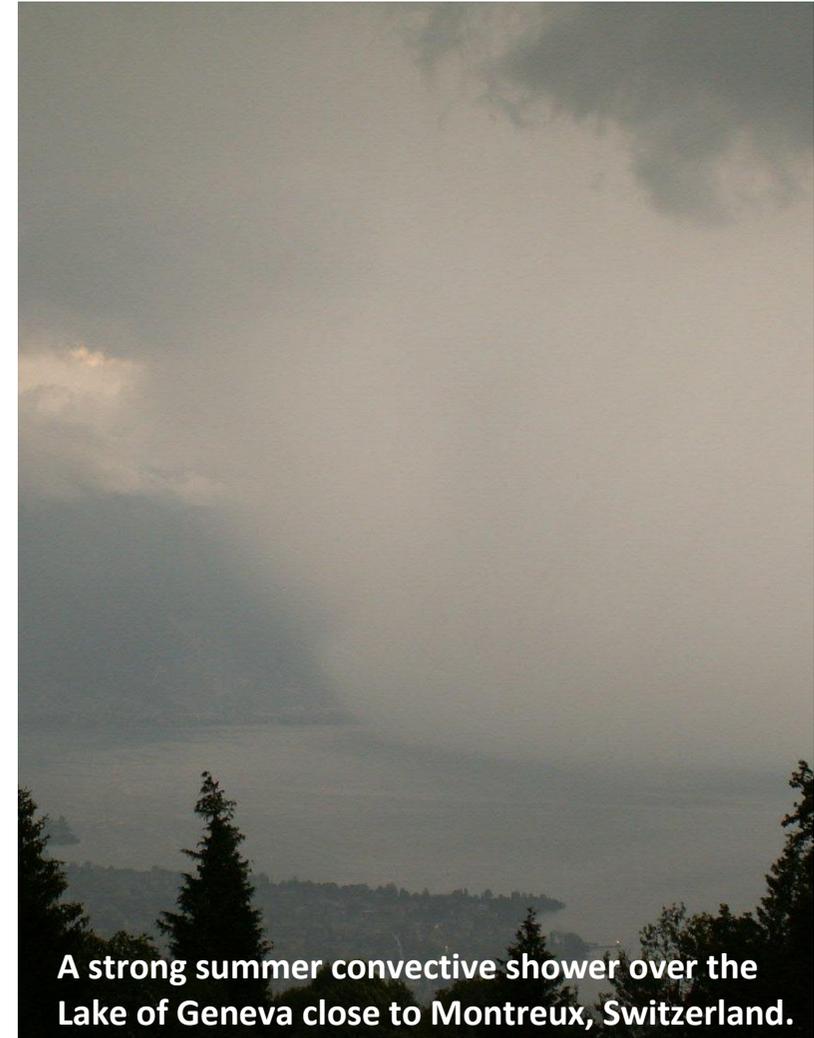


increased mass-movement activity as a consequence of predicted climate change, impacts can hardly be detected currently in observational records.

Added value from the ACQWA project: One of the most obvious consequences of climate change at higher elevations is the glacier downwasting and related formation of ice-marginal lakes, ice avalanches and gravitational processes originating from the debuttressing of previously glacierized walls and hillslopes. Glacier downwasting is likely to promote many rock slope failures at rather short future time scales, probably in the order of decades. Important effects of climate change on slope stability are also related to the warming and thawing of permafrost. Slopes currently underlain by degrading permafrost will probably become less stable at progressively higher altitudes with ongoing climate change. The probability of rock instability and the incidence of large ($>10^6 \text{ m}^3$) rockfalls will likely increase in a warming climate. A large number of recent slope failures have been documented in permafrost areas, related to increasing temperatures.

Policy-relevance of this research: Changes in sediment supply and land-use are further key determinants for mass-movement frequency and magnitude. Recent observations in the Swiss Alps indicate that sediment supply can in fact change significantly as a result of permafrost degradation of rock and scree slopes or mass movements related to other processes. As such, warming has been reported to exert indirect control on debris-flow magnitude and frequency through the delivery of larger quantities of sediment into the debris-flow channels under current conditions than in the past. The volume of debris flows in much of the Swiss Alps has risen by one order of magnitude since the early 20th century and is likely to further increase with ongoing permafrost degradation. The actual triggering conditions of debris flows have been shown to occur less frequently today as compared to the most of the 20th century, and are not expected to increase in the future. Despite uncertainties, recent developments at high-elevation sites have clearly shown that the sensitivity of mountain and hill-slope systems to climate change is likely to be acute, and that events beyond

historical experience will continue to occur as climate change continues, thereby calling for a critical review of existing hazard maps.



A strong summer convective shower over the Lake of Geneva close to Montreux, Switzerland.



PART 3

POTENTIAL IMPACTS



Murillo de Gállego at the foot of the Pyrenees, in the Aragón River basin



Multiple impacts

Climate and land use impacts on water availability and management: The case of the Aragón river basin, Pyrenees

Overview: A warming between 1-2°C and a decrease of precipitation between 5-20% is projected for the Spanish Pyrenees according to climate model simulations (A1B scenario) for the 2021-2050 period. A noticeable increase of warm events during winter months is also expected in the region. In the Pyrenees, an increase of 1°C implies a 20% decrease in snow accumulation at 2000 m above sea level. This sensitivity increases at lower altitudes and decreases at upper elevations.

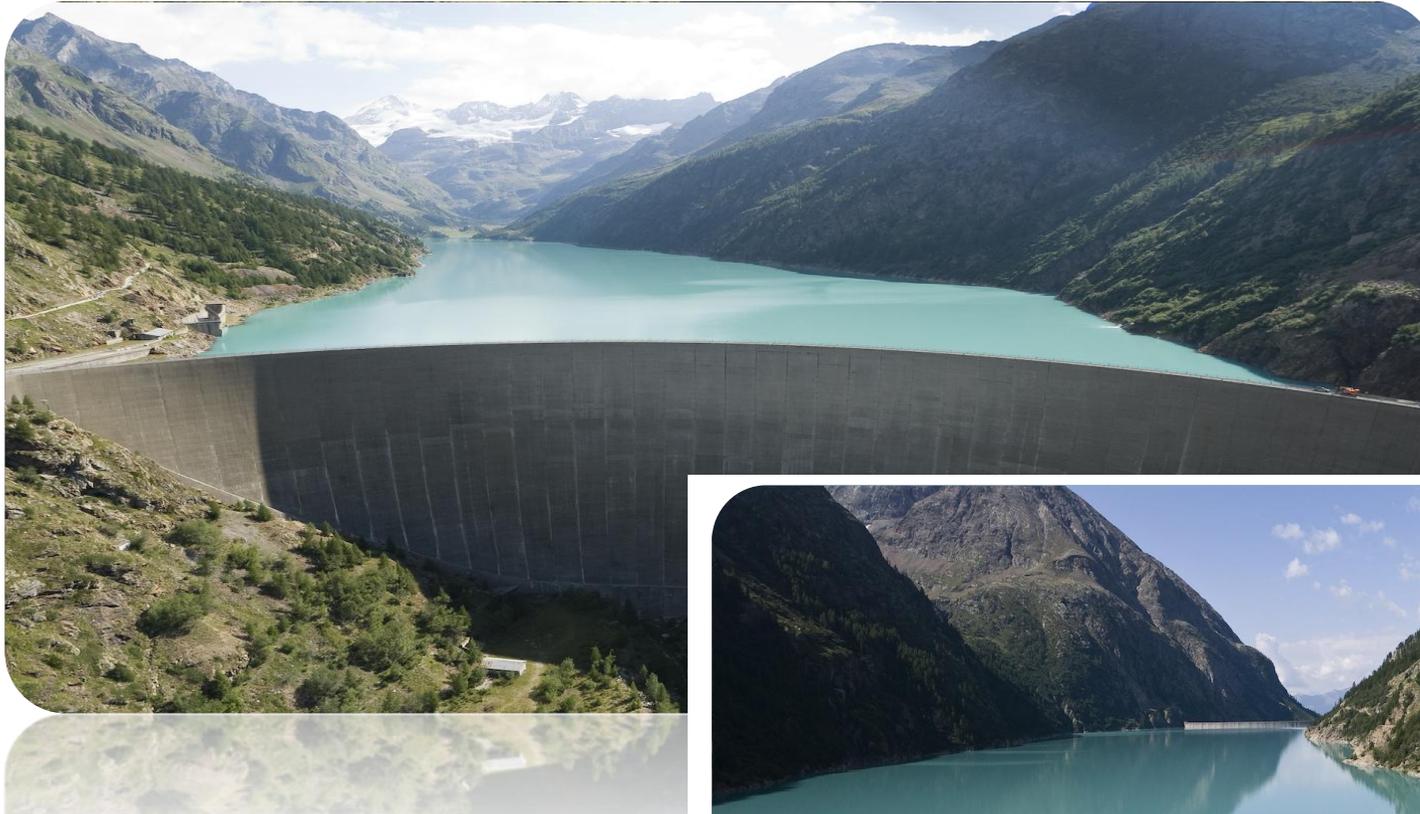
According to observed land cover change and the analysis of current aerial photography and remote sensing data, a scenario of land cover for the middle of the 21st century in the Pyrenees has been developed. Shrub areas are projected to evolve toward pine forests, with a 100 meters rise in the tree line and an increase of the shrub areas in the subalpine areas.

Increased vegetation in the basin could decrease annual stream flow in the Upper Aragón river basin by 16%, mainly in early spring, and autumn. Projected climate change could decrease annual stream flow by 13.8%, mainly in late spring and summer. Combined effects of forest regeneration and climate change may thus reduce annual stream flows by 29.6%. Simulating the management of the main reservoir of the region using the modeled hydrological data, it is likely that serious difficulties to meet the current water demand, based on its current storage capacity (476 hm³) will emerge. If the current project to enlarge the reservoir to a capacity of 1059 hm³ is completed, the potential exists to apply multi-annual stream flow management, which will enhance the capacity to maintain the current water supply. However, under future climate and land cover

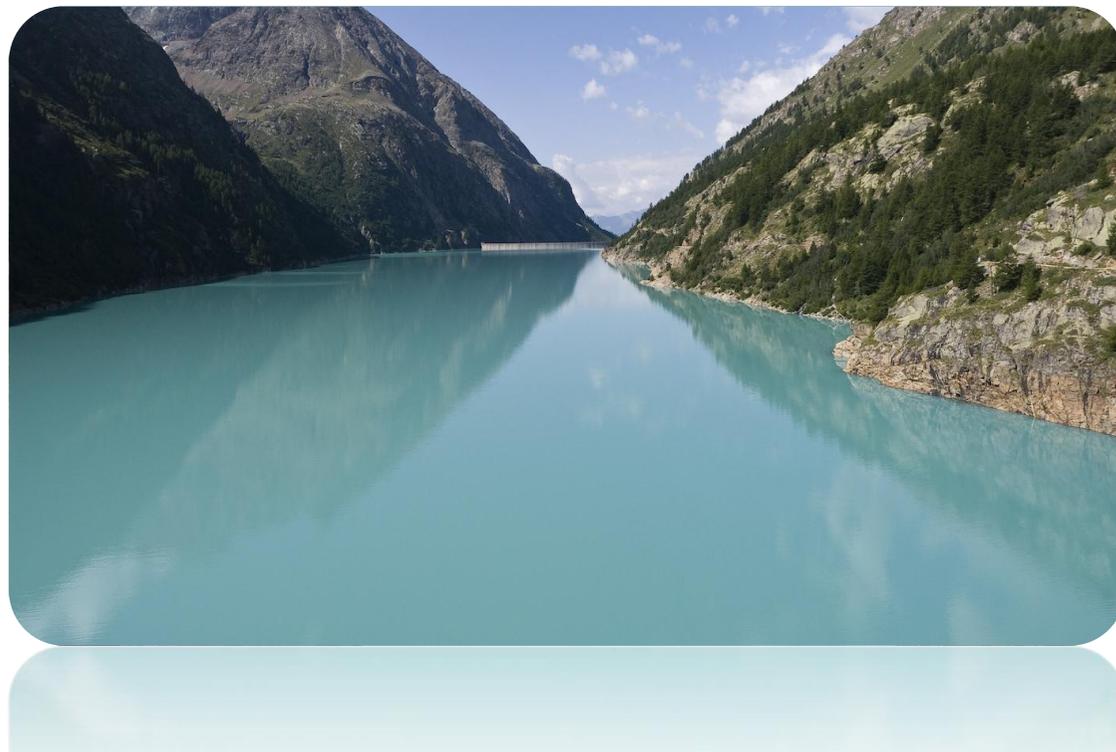
scenarios, reservoir storage will rarely exceed half of the expected capacity, and the river flows downstream of the reservoir may be dramatically reduced.

Added value from the ACQWA project: This is the first time that Pyrenean hydrology is simulated combining both climate and land cover change. It has enabled to assess the magnitude and the seasonal character of each type of change and their joint effect. In addition, the simulation of the management of large dams using hydrological model data, enables an assessment of the feasibility of meeting current water demand in the future.

Policy-relevance of this research: Water availability is probably the main constraint for the development of modern agriculture, industry and tourism in the Ebro valley. The work developed within the ACQWA project provides robust information to water managers and policy makers concerning the response of river flows under projected environmental change. The study provides advance warning concerning limitations to maintain current water demand even if the regulation capacity is increased in headwater areas. Moreover, the study suggests that controlling land cover may be a mitigation strategy to minimize the probable reduction of available water resources.



The Place Moulin reservoir in Valle d'Aosta, the largest dam complex in the region





Impacts on hydropower

SUMMARY OF KEY FINDINGS

- Variability in glacier retreat patterns (size, aspect, shape, debris cover, etc.) has consequences for the management of hydropower plants and dams, which depend primarily on snow- and ice-melt.
- Reduction in surface water flows and seasonal shifts in water availability (more availability of water in the earlier months of the year and a longer summer period with lower run-off) will impact hydropower. Climate change also indirectly affects electricity load because energy consumption varies with air temperature.
- Technological, economic and behavioural changes in the electricity system are, however, expected to exert a stronger impact on hydropower.
- In the Po region, greater variability in river flows and decrease in snow fall will affect the filling of hydropower reservoirs (e.g., decreasing ability to use all the storage capacity) and increase the inter-annual variability of electricity production.
- 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.



The Swiss Rhone catchment

Overview: This research provides an analysis of the hydropower future in the context of climate change, opening of the electricity market to competition, decarbonisation of the energy system and, in some countries, even phasing out of nuclear energy. The case study of the hydropower installation of Mattmark, located in the Rhone catchment represents the focal point of the analysis conducted in the context of ACQWA. In addition, the study encompasses Swiss and European dynamics, in particular those related to energy policy and markets. The first part of the research, devoted to Mattmark, provides quantitative results, whereas the Swiss and European analyses are mainly qualitative.

Added value of the ACQWA project: The main interest of this study is to highlight the link between climate change, electricity markets and energy policy. In particular, it shows how electricity generation is affected by climate change, the opening of the electricity market to competition, as well as the development of micro and super-grids, new storage technologies and intermittent energy resources such as solar and wind energy. These factors also influence the added value created by hydropower, which represents an important source of revenue in mountain regions. The analysis takes into consideration the electricity demand, which is affected only modestly by climate change. The impact of its variation on the wholesale power market is estimated by means of econometric tools. Microeconomic models and techniques based on operational research are used to simulate the markets' behaviour, hydropower reservoir management, as well as electricity generation.

In Figure 19, pink boxes represent the drivers that are transforming the electricity system, which includes centralized and decentralized generation; storage services; consumption; supply and demand; flows of power through the electric lines (plain lines) and flows of information, notably price signals (dotted lines). Spot, future, balancing and ancillary services markets will determine the value of hydropower. Climate change will affect hydropower because of the possible

reduction in surface water flows and seasonal shifts in water availability. The technological, economical and behavioural changes in the electricity system are, however, expected to exert a stronger impact on hydropower.

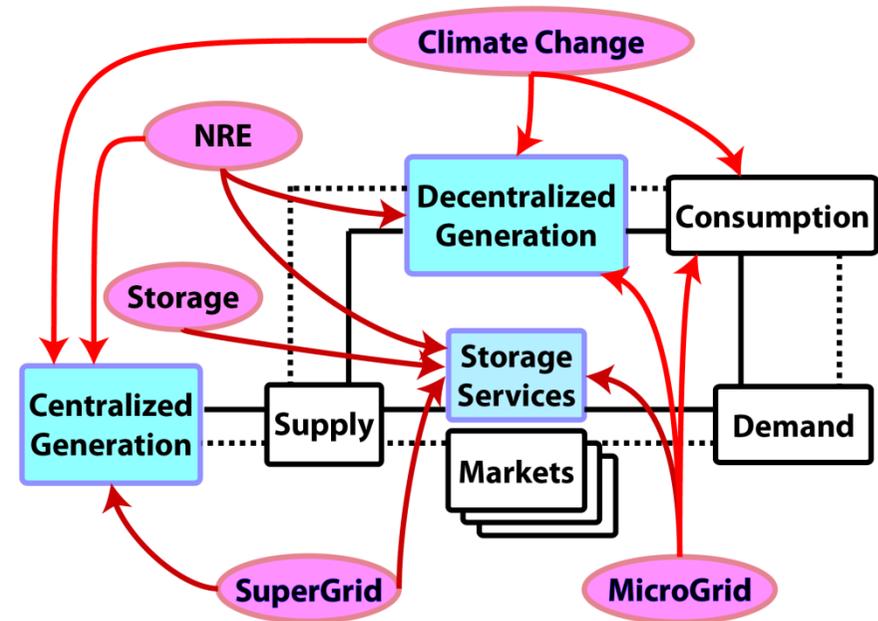


Figure 19: Multiple constraints on electricity markets

Policy relevance of this research: The outcome of the research conducted on the Mattmark site provides key information to decision-makers about the factors that will determine the future output and value of hydropower. Despite the margins of uncertainty, public bodies and private or public companies may use this information in the definition of their policies and strategies. The particular case of the renegotiation of the concessions for water rights, which represents a topical issue in several Alpine regions, is particularly relevant. In the case of Switzerland, most of the concessions will come to an end between 2030 and



2060. It should be mentioned here that, thanks to its flexibility, hydropower and reservoirs play a very important role in ensuring the security of electricity supply and the network's stability in Europe.

The Po Basin

Overview: Climate change is affecting hydropower production in two ways: directly, through changes in precipitation and, as a consequence, in inflows; and indirectly through the electricity load because energy consumption varies with air temperature. This could be very important in determining the management of hydropower reservoirs and may cause conflicts with concurrent water uses.

In particular, reservoir management is aimed to provide the water resource when it is needed, transforming the natural regime, with its modulation across the year and its random fluctuations, in a regulated and more useful flow.

The main results can be summarized as follows:

1. A large local variability in electricity production, which follows an analogous rainfall pattern: a reduction of 10% is estimated in the Val d'Aosta while a 20% increase is expected in the Toce valley;
2. The monthly modulation of power production throughout the year is expected to change: in both areas, the greater variability in summer inflows will affect the filling of hydropower reservoirs and, in some years, it will not be possible to use all the storage capacity.
3. the interannual variability of production is projected to increase.

All these effects are mostly the consequence of greater variability in river flows and the decrease in snow fall.

To complete the study of effects on hydropower production the other relevant forcing was studied, i. e., variations in energy prices.

The two Italian small case studies are very similar: in general, larger volumes of water are stored in winter and greater quantity of water are used in Spring, corresponding to a higher energy production in this period.

Added value from the ACQWA project: Thanks to the collaborations of the ACQWA project, universities, research centers and private companies have had the possibility to deal with a high quantity of data produced by climatological and hydrological models at large spatiotemporal scales. These data allowed the implementation of detailed management models, simulating the management of hydropower plants. Large areas of north-western Italy were analyzed and an assessment of the impacts of climatic change on the water and electricity sectors in these zones has been made available.

Policy-relevance of this research: An increase in the variability of water availability may lead to a number of profound consequences: the exploitation of existent hydropower plants decreases due to the increase of inactivity time (for run-of-river power plants) and the stability of the electric system (the transmission grid) could be endangered because of the growth in the randomness of the source of hydropower. Moreover, the greater water variability will affect other uses of the resources (for instance agriculture) and the water deficit of the valley is expected to increase.

The increase of the regulated volume is a first possible reaction to climatic change; it is useful in order to smooth oscillations in river flow and provide water when it is needed. This measure makes sense for two reasons: the first is that a greater variability calls for a greater storage capacity; the second is that with the decrease in snow fall a natural storage is lacking and it could be appropriate to restore it artificially.

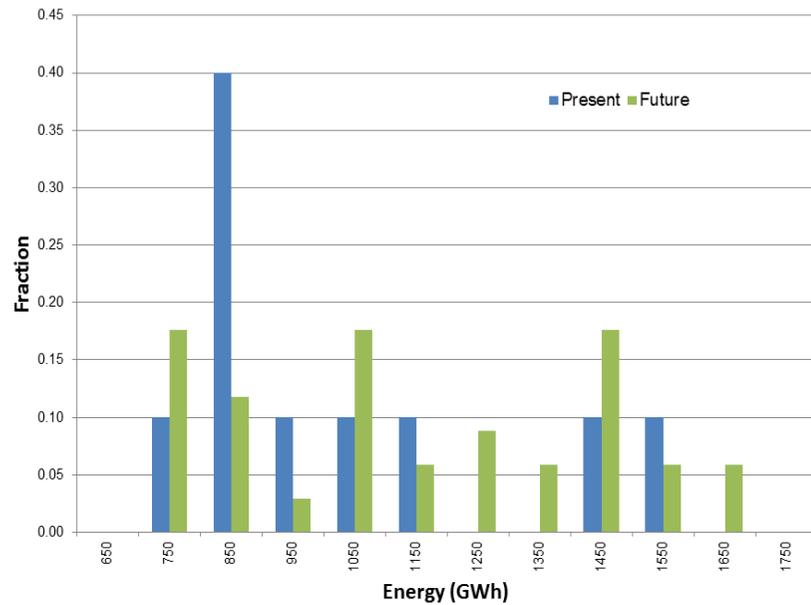


Figure 20: Frequency distribution of yearly production – Toce network

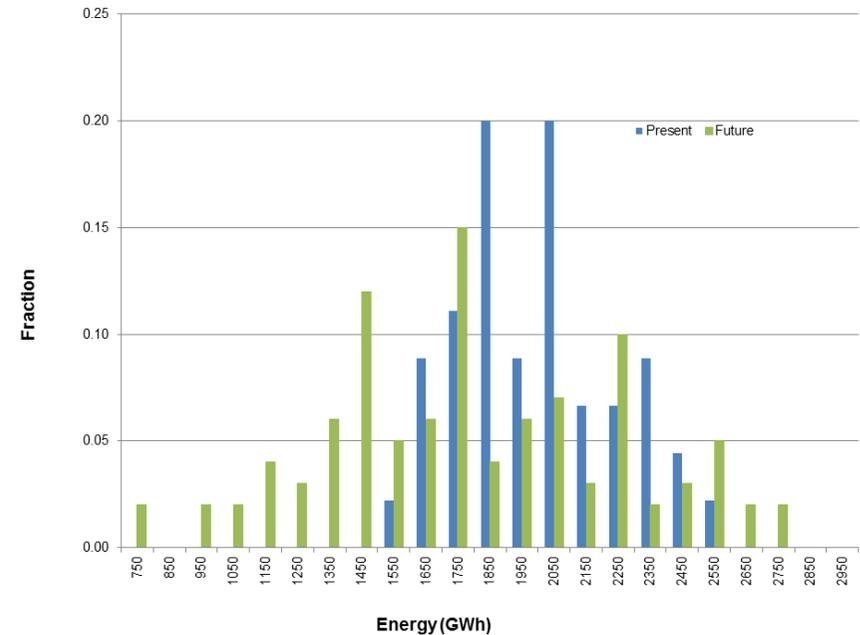


Figure 21: Frequency distribution of yearly production – Valle d'Aosta network

However, new storage capacity implies the construction of new dams and reservoirs that could modify heavily the natural landscape of the Alpine region and are not easily accepted by local communities. This potential for conflict calls for the development and implementation of methodologies and processes to increase the adaptive capacity of water governance and management systems. ACQWA results could be used as an important aspect to be considered in decision making procedures regarding the development of new infrastructures for the water sector.



Impacts on agriculture

SUMMARY OF KEY FINDINGS

- Until 2050 major agro-climatic risks will likely be caused by high temperatures rather than by increased drought (negative effects on both crop and livestock production).
- With increasing temperatures, water consumption through crop evapotranspiration increases is likely to lead to additional irrigation demands to maintain optimal yields (e.g. +10% in July at Visp across a range of climate scenarios up to 2049).
- High demand for water for irrigation will put additional pressure on small rivers in catchments with little or no water supply from glaciers, while larger water sources in valley may not be subject to the same extent of variability.
- In drier areas with low summer precipitation (e.g. valley floor and the south-facing slopes), potential water shortages for crop growth would be likely, requiring more irrigation to maintain optimal crop yields (max. +35%).
- In extremely dry years irrigation requirement could potentially exceed 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.
- In the upper Rhone valley, improved water management should include both regulations regarding the allocation of water to different users of the same source, installation and management of reservoirs, and technical measures to improve the efficiency of irrigation by avoiding losses of distribution systems, evaporative losses, and excessive runoff due to over-application of water.
- Shifts in intensification of grassland use may have negative consequences for other ecosystem services such as biodiversity, soil carbon storage, and nitrogen retention.



The Swiss Rhone catchment

Overview: In the Swiss Rhone catchment, irrigation has historically been important. Today, about 11'000 ha of land is irrigated with over half occupied by grasslands used for livestock production, followed by orchards and vineyards. This allocation of irrigation reflects the economic importance of the production of livestock and permanent crops, while arable crops play a minor role.

Over the past decades, a trend was identified towards a higher frequency of extreme droughts on timescales shorter than 2 months, whereas for longer timescales, no clear indications of a change over time could be found. For the future, the mean of several agro-climatic indices even suggest a shift towards warmer and rather wetter mean conditions during the growing seasons, but an increase in risks caused by high temperature (i.e., heat stress). The thermal growing season becomes longer, with potentially positive effects on pasture and livestock production, most pronounced at mountain sites, whereas at the valley bottom, a trend occurs towards increasing risks of frost in permanent crops due to an asynchronous change in the beginning of the growing season and late frost occurrence, and in heat stress for livestock.

With increasing temperatures, water consumption through crop evapotranspiration increases, thus leading to additional irrigation needs to maintain optimal yields. This concerns much of the lower part of the valley, but also the pasture-dominated south-facing slopes, especially on soils with low water holding capacity. Simulations reveal a moderate average increase in water requirement for irrigation in 2021-2050 relative to 1981-2009. In the currently driest areas, additional potential water requirements from 1981-2009 to 2021-2049 would range between 0 and +200 mm per average growing season, depending on the climate scenario. During extremely dry years, such as 2003 or 2011, the increase would be much higher and could exceed the water availability

in surface waters of smaller catchments with a nival runoff regime. An example would be the catchment of the Sionne (27.7 km²) where water is drawn through water channels ('Suonen') for grassland irrigation, and where discharge is controlled by snowmelt and rain. A much reduced area could be irrigated under these low-flow conditions, which may become more frequent in the future. At the catchment-scale, the estimated mean total water requirement is 32×10^6 m³ per year (1981–2009), and a 45% increase during the 2003 European heat wave in the driest area of the catchment. With an extreme scenario, the increase amounts to 44% by 2050, which is consistent with the values of 2003.



Vineyards of the Lavaux (UNESO World Heritage site), on the banks of Lake Geneva, part of the Rhone catchment



Added value from the ACQWA project: A new and simple approach was developed for estimating the spatial and temporal variability of seasonal net irrigation water requirement. The approach could be extended to other applications, including assessments of the impacts of climate change in combination with land-use change. In collaboration with other teams in the ACQWA project providing high-resolution, downscaled climate information, it was possible for the first time to map changes in irrigation water requirement in response to different climate projections for the Swiss Rhone catchment. This helped to identify hot spots of change and areas of possible water shortages. Moreover, the climate data provided the basis to evaluate additional risks such as heat or frost.

Policy relevance of this research: Coping with climate change in agriculture requires knowledge of possible trends in agro-climatic conditions, with a focus at the smaller scales such as catchments or sub-catchments where decisions are taken. At those scales, risks from water shortage during parts of the season are likely to become more important in the long-term future, particularly in view of a drastic decrease in glacier volume and snow cover. The methodology developed in this project can help to identify emerging water conflicts. Given the importance of grazed pastures in the mountain zones for their economic, ecological and cultural role, it can be expected that agricultural policy will continue to support the maintenance of this extensive form of agricultural production, which requires irrigation. In other parts of the valley, maintenance or even expansion of the production of high-value crops such as grapevines and fruit trees, or even vegetables, would continue to use water for irrigation. However, the amount is much smaller than for pastures, given the smaller surface area concerned, and the shorter length of the irrigation period. Moreover water resources at the valley bottom are much larger and may not be subject to the same extent to inter- and inner-annual variability on the timescale considered because the dependence on rain and snow is less than in sub-catchments with a nival regime. And, technical measures to optimize and control irrigation, or building reservoirs would be easier to implement.

Thus, in the shorter-term, the demand for water for irrigation will increase and put pressure on smaller rivers in catchments with little or no water supply from glaciers, particularly in years with limited precipitation and snowmelt during springtime. In the sub-catchments concerned, water management will play an even more essential role under future climate conditions than in the past. This improved water management should include both regulations regarding the allocation of water to different users of the same source, installation and management of reservoirs, and technical measures to improve the efficiency of irrigation by avoiding losses of distribution systems, evaporative losses, and excessive runoff due to over-application of water.

An important result of this assessment is that until 2050 major agro-climatic risks under climate change will likely be caused by high temperatures rather than by increased drought. Situations with high temperatures may have negative effects on both crop and livestock production. Measures to cope with this risk could include the use of additional water for cooling purposes, shifting crop cultivation windows, and shifts in cultivar selection in both arable crops and permanent crops (grapevines, fruit trees). In addition, extending the grazing period and shifting of grazing zones to higher and/or cooler parts of the catchment could help to avoid heat stress in animals. However, such shifts in intensification of grassland use may have negative consequences for other ecosystem services such as biodiversity, soil carbon storage, and nitrogen retention. Thus, coping with heat stress in livestock production will require careful consideration of the sensitivity of alpine grassland ecosystems to intensification.



The Po Basin

Overview: A basin-wide enquiry for the Po Basin has looked into the optimal policy that might facilitate adaptation to climate change in agriculture, in particular policies that can help to smooth water input fluctuations. The different roles of farmers and the public sector in adapting to these changes have been addressed. The first and most fundamental level of adaptation to climate change in agriculture occurs at the level of the local farmer. Farmers undertake strategies to adapt to the form of climate change that they are able to foresee, through observation of the recent trends in indicators such as average temperatures and average precipitation.



Vineyards in Piemonte, part of the Po river catchment

However, they can do little to respond to the greater uncertainty inherent in climate change. Farmers' adaptation to expected climate change will often take the form of investment in assets to shift water temporally, using locally appropriate water storage techniques. It might also be possible for water management to be pursued through more efficient irrigation practices.

Because of the low costs and relative abundance of the water resource in the Po basin, farmers have traditionally relied on inefficient irrigation methods, which are still one of the main causes of waste of fresh water resources. Local farmers adopt strategies to cope with expected climate change, but the important question for policy makers concerns the role of governance in supporting adaptation.

Added value from the ACQWA project: A key question here is the role that remains for policy in light of local adaptation. Evidence is given by this study that there are some impacts of climate change that farmers' adaptations do not reach at present. Despite the farmers' observed investments to adapt to mean changes in climate, variability in climate continues to impact crop yields. Table 2 shows the results of a simple correlation analysis of the relationship between variability in temperature, precipitation (during the months March to August) and agricultural yields in the Po basin.

Log Yields	Precipitation anomalies	Temperature anomalies
Maize	-0.16***	0.02
Barley	-0.28***	-0.15***
Soft Wheat	-0.43***	-0.1*
Sugar Beet	-0.21***	-0.2***
Soya	-0.23***	0.08

Table 2: Correlation between crops yields and standard deviation of precipitation and temperature. Significance Levels of the correlation coefficients at: ***1%; **5%; *10%.



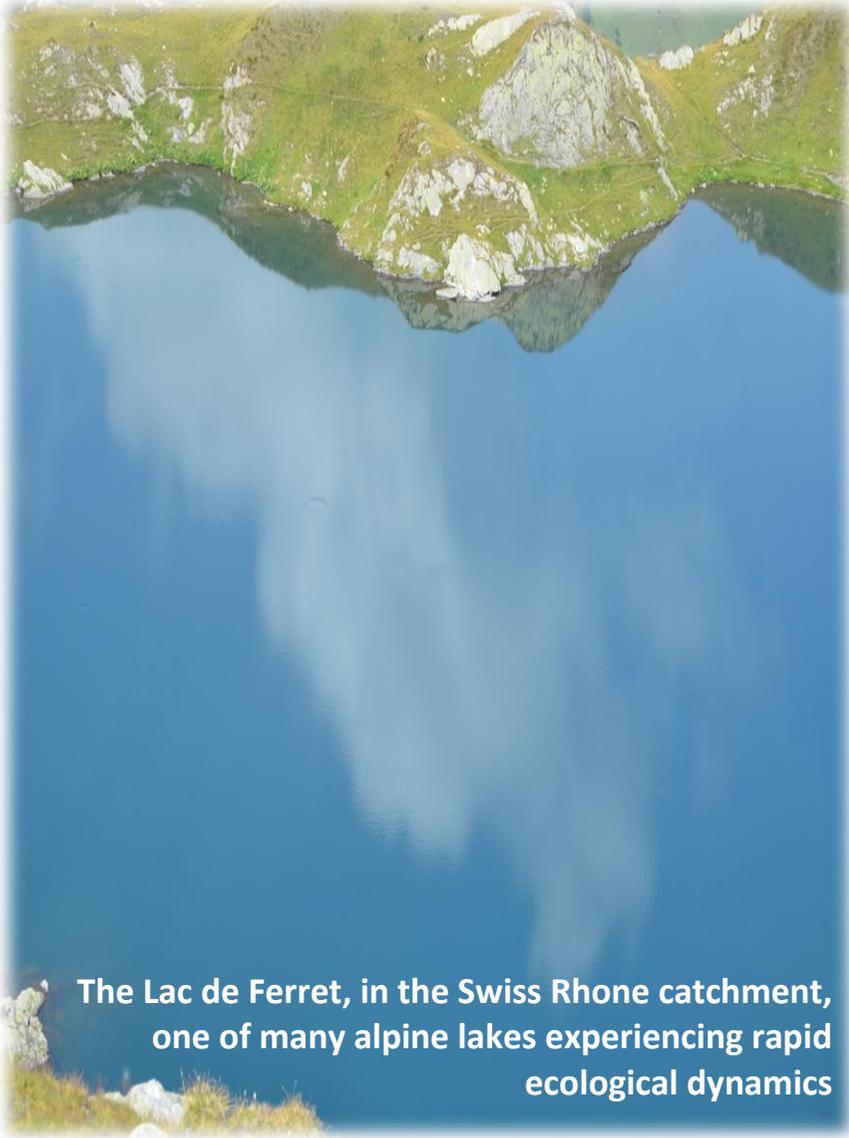
The negative correlation between agricultural yields and observed anomalies indicates that agricultural production has suffered when unanticipated climatic variability occurs. In short, farmers' adaptations appear to be based on individual (farmer-based) forecasts deriving from current trends in observed weather patterns, but are not responding to the increasing variabilities.

Policy relevance of this research: Policy intervention must deal with the residual uncertainty remaining after local adaptation to climate change. The role of policy will thus be to address this residual uncertainty, investing in institutions and infrastructure. The policy maker should see its function as: a) aiding and facilitating farmer adaptation; b) ascertaining residual uncertainty and change unmanaged by local farmers; and c) adopting policy interventions that deal with the residual problem. The Po basin is characterized by high territorial heterogeneity and a complicated governance structure in the water management sector. Roles and responsibilities often overlap and are not clearly defined between different levels of governance and a multiplicity of institutional actors. Furthermore, rules regarding water access and abstraction have traditionally been weakly implemented. Despite these institutional problems, there are clear policy directions to consider for addressing the remaining variability. One approach would be to consider the integration of all water resources across the entire watershed (at a particular point in time) – this is the point of “water trading”. Another approach would be to try to smooth variability by means of integration of water across time – this is the point of “water storage”.

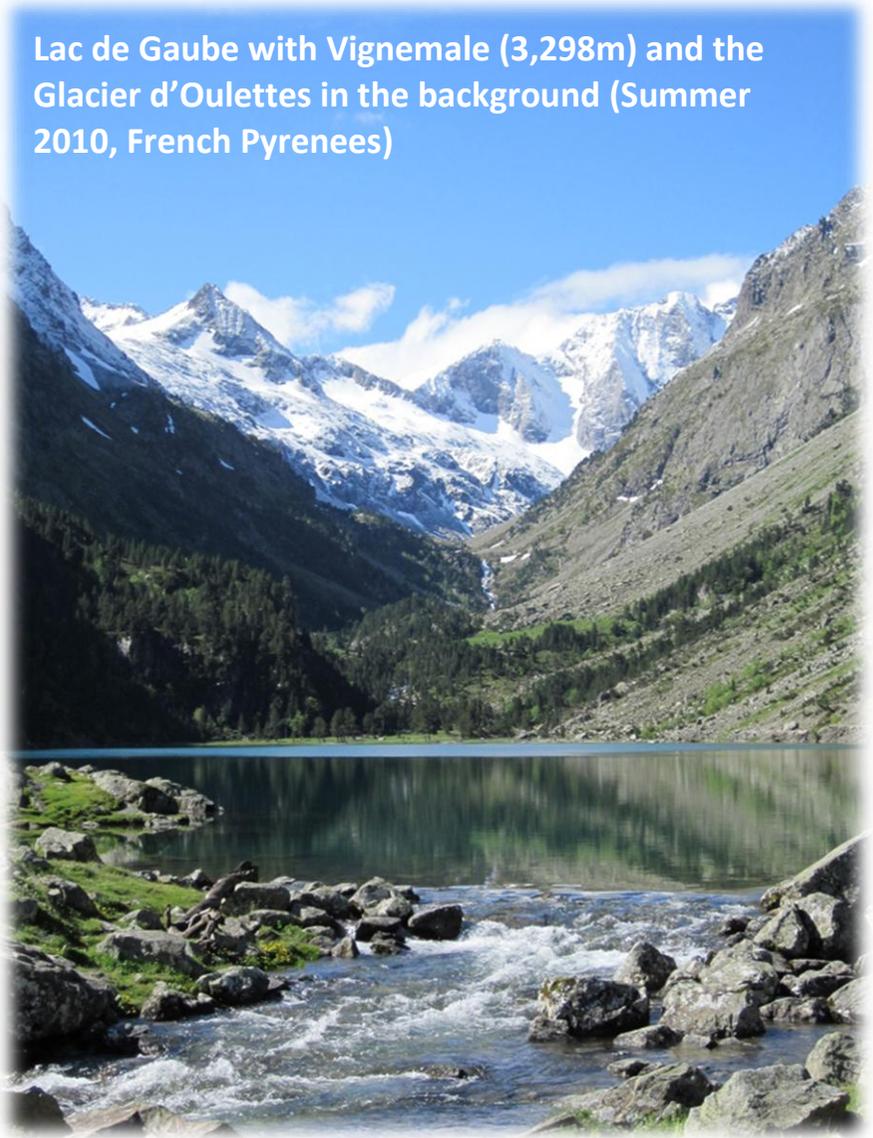
Spatial interventions entail water trading across the basin, to move water resources from water-abundant areas to areas in need. To assess the viability of water trading, we analyzed spatial correlation patterns in monthly rainfall across

the basin over the last thirty years. Rainfall correlation is significant, which reduces the attractiveness of water trading. Spatial water management is also complicated by multiple management regimes along the watershed.

Intertemporal interventions (water storage) constitute another way policy can intervene to address residual uncertainty. Farmers' adaptation may take many forms: in the Po basin investments in storage techniques are often observed. However, it is frequently the case that storage capabilities at farmer's level are not enough to cope with residual uncertainty in climate, and in particular with unexpected variability in rainfall. In the Po valley, surface water is generated both by natural stocks of water, such as glaciers and alpine lakes, but also by many artificial dams. Upstream entities in charge of managing these forms of water stock could consider the interests and needs of the downstream sectors in their decisions about the timing of water release. However, the Alpine dams have been constructed mainly for hydroelectric production and their management decisions in terms of water release are currently not coordinated with the needs of the agricultural sector. One of the main weaknesses of the water resources management sector in the Po basin is that its governance and institutional framework are very complex. With this consideration we assert that in some instances the water manager shall implement jointly spatial and intertemporal interventions, through integrated management. A better institutional and governance framework shall impose the usage of existing water stocks which takes into account the prerogatives of different stakeholder. The Po Basin study confirms that the direct and indirect impacts of higher precipitation variability over the next 50 years are likely to increase costs of any poor water management.



The Lac de Ferret, in the Swiss Rhone catchment, one of many alpine lakes experiencing rapid ecological dynamics



Lac de Gaube with Vignemale (3,298m) and the Glacier d'Oulettes in the background (Summer 2010, French Pyrenees)



Impacts on aquatic ecosystems

SUMMARY OF KEY FINDINGS

- Increased temperature, seasonal precipitation shifts, reduced ice cover and ice melt are likely to have significant implications for aquatic biodiversity: increased abundance of larger predator species, increased primary and secondary productivity, increased local diversity, decreased regional diversity.
- Successful application of a water source approach in a changing cryosphere across multiple river basins highlights its potential for use in future alpine conservation planning.
- Cases from the Pyrenees (sentinel site) and the Swiss Alps highlight that although climate signals are broadly similar, the predicted hydrology – habitat – ecology responses are varied and are a function of cryospheric river flow buffering potential (i.e., glacier size).
- A shift is proposed to move provisions and policy guidance on conservation approaches from focusing on taxonomic units to functional units.
- New baselines should be set based on ecosystem functioning rather than taxonomic diversity.
- To better align principles and provisions in conservation and water resources legislation and policy with the projected impacts of climate change on freshwater ecosystems, three key shifts are proposed: (i) move from focusing on direct and point source impacts to diffuse threats; (ii) recognise flexibility and dynamism in the system, rather than aiming to control static ecosystems; (iii) improve integration and synergies across different policy frameworks that impact conservation.



Impacts on mountain lake ecosystems

Overview: During the ACQWA project, measurements of the physical, chemical and biological parameters in 20 high-altitude, ultra-oligotrophic lakes in the Gran Paradiso National Park (PNGP) were undertaken. All these lakes are characterized by extreme seasonality; most are naturally fishless, while some were stocked with fish about forty years ago. Both fishless and stocked lakes were sampled in order to determine the effects of introduced fish and of the interplay between the introduction of alien species, strong seasonality and shifts in environmental conditions. Among the different measurements, zooplankton densities at different depths in order to gain insight on their vertical distribution, their migratory behavior along the water column and the response of zooplankton to vertical abiotic gradients (e.g., light intensity and UV gradients). The PNGP measurements were complemented by the development of deterministic one-layer models to simulate the dynamics of high-altitude lake ecosystems, in order to estimate the response of the lake ecosystems to climate and environmental change (temperature, duration of ice cover, etc). These observational and modeling studies have enabled some of the first quantitative determinations of the effects of introduced fish and of the interplay between stocking and environmental change.

Added value from the ACQWA project: Quantitative and repeated measurements, complemented by appropriate mathematical models, have up till now been scarce for high-altitude Alpine lakes. The work made during the ACQWA project has led to a new set of measurements and new insight into the dynamics of Alpine lake ecosystems. The new models developed for such ecosystems can now be used to estimate the response of high-altitude aquatic ecosystems to climate and environmental change.

Policy-relevance of this research: All lakes are inside the highly-protected PNGP, whose management and conservation policies in the face of climate change will be based on the results of these studies. In particular, the analysis of the effect of

alien species has led to an experimental fish eradication program for some of the stocked lakes. A new LIFE+ project on such themes, based on the results of the research conducted during the ACQWA project, has been proposed and granted. Furthermore, as an additional outreach activity, a photographic exhibition on high-altitude Alpine lake ecosystems has been prepared for public audiences

Impacts on Pyrenean aquatic ecosystems

Overview: In mountainous river basins, the water source balance (i.e., the contribution of rainfall, glacier-melt, snowmelt, and groundwater to flow) is extremely sensitive to climate change. Projected warming is likely to alter stream flow quantity/quality regimes and modify in-stream physico-chemical habitat. As a result, biodiversity patterns of alpine running water organisms are highly likely to be altered, as vulnerable species must either adapt physiologically and/or genetically or migrate to more suitable habitats to persist.

As part of the ACQWA project an inter-disciplinary approach was adopted to investigate alpine stream ecosystem responses to climate change. Both the drivers of change (i.e., climate) and responses to change (i.e., hydrology – habitat – biota) were quantified using a combination of scenario simulation, space for time substitution surveys and in-situ experimental work. Macro-invertebrate community structure and function, population genetics, habitat characteristics and water source contributions were recorded at 26 sites representing a gradient of glacial influence, across five river basins in the French Pyrenees. Contemporary river flow, habitat, taxonomic and genetic patterns were related to both glacier cover and melt-water contribution to bulk discharge. Downscaled climate data was then used to drive (i) a watershed simulation (TOPKAPI) of river flow and glacier/snow melt dynamics and (ii) a water temperature regression model. Temperature and hydrological projections were then linked to observed patterns to predict future hydro-ecological change (see Figure 22 for the scenarios).



Further work, to improve understanding of finer scale hydrological and biological process, investigated; (i) the response of an alpine spring community to the introduction of a large bodied invertebrate predator (predicted to expand its range) and (ii) the inter-annual variability of the heat budget and thermal dynamics of a glacier-fed river reach.

Added value of ACQWA project: Until now application and testing of the water source contribution approach as a hydro-ecological management tool, has been limited to single river basins. Results from this study highlight the utility of this approach for both management and prediction of climate driven ecosystem change. Furthermore, knowledge transfer between project partners enabled the successful completion of watershed simulations for a glacierized river basin in the relatively data poor Pyrenees, where until now few simulations have been conducted. This provided a unique insight into future hydrological and physico-chemical habitat change and the potential implications for biodiversity. Quantification of melt-water contribution enabled the identification of climate sensitive macro-invertebrate taxa which are expected to exhibit considerable range contraction as glacier retreat. Trait profiles of glacial stream taxa were also recorded and were shown to have the potential to act as indicators of changing water source dynamics (i.e., reduced glacier contribution to discharge), particularly when comparing sites from multiple biogeographic regions. Improved process understanding from experimental work and high resolution hydro-meteorological observations could prove valuable for further development of deterministic temperature models and species distribution models.

Policy-relevance of this research: The Pyrenees represent the southern limit of contemporary glaciation in Europe, and only small cirque glaciers remain of the extensive ice cover which existed during the Little Ice Age. Thus, findings here can be viewed as a future analogue for mountain ranges which currently have significant glacier cover but which will shrink in the future. The successful application of the water source approach in a changing cryosphere across multiple river basins highlights its potential for use in future alpine conservation

planning. Furthermore, the coupling of hydrological simulation and space for time surveys has a potential to inform future baseline conditions and could prove valuable for determining appropriate climate adaptation conservation strategies.

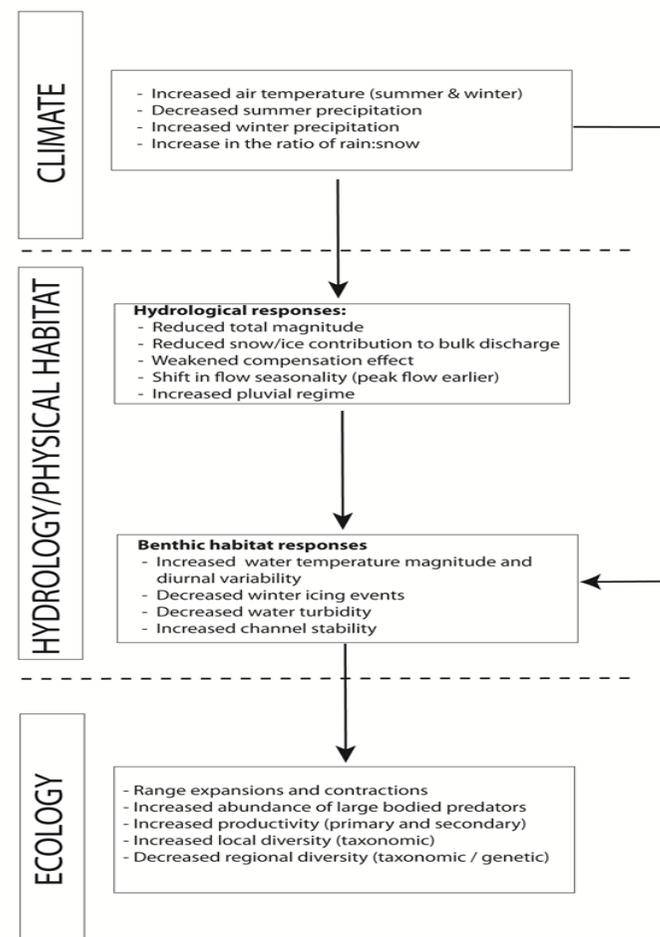


Figure 22: Flow diagram outlining the projected change (2050 horizon) to climate – hydrology – habitat – ecology for the Taillon-Gabietous catchment, a small glacierized river basin in the French Pyrenees.



Impacts on mountain forests

SUMMARY OF KEY FINDINGS

- Sensitivity of mountain forest ecosystem services (ES; carbon storage, runoff, timber production, diversity, and protection from natural hazards) to a 2 °C warmer world depends heavily on the current climatic conditions of a region, the strong elevation gradients within a region, and the specific ES in question.
- At low and intermediate elevations large negative impacts will occur in dryer-warmer regions, where relatively small climatic shifts result in negative drought-related impacts on forest ES.
- Some services such as protection against rock-fall and avalanches are sensitive to 2°C global climate change, but other services such as carbon storage remain reasonably resistant. A 2 °C increase of global mean temperature therefore cannot be seen as a universally “safe” boundary for the maintenance of mountain forest ES.
- At higher elevations and in regions that are initially cool-wet, simulations suggest that forest ES will be comparatively resistant to a 2° temperature rise.
- Analysis provides pivotal information for ecosystem management by pinpointing regions and ES that are most likely to be particularly sensitive, thus allowing ecosystem managers to concentrate their efforts and to spend the limited financial resources in the most effective way.

Overview: Climate change has the potential to substantially alter the provisioning of essential ecosystem services (ES), and mountain regions are likely to be both particularly vulnerable and heterogeneous in their response to climate change. To date, few studies have attempted to quantify the impact on mountain ecosystems under a wide range of climate scenarios, including novel “2° scenarios” that are based on the assumption of an early stabilization of greenhouse gas concentrations in the atmosphere. Similarly, although mountain ES are crucial both locally (e.g., forest-mediated protection of human infrastructure from avalanches or rockfall) and regionally (e.g., impact of ecosystems on runoff generation), there is a scarcity of studies focusing on shifts in ES.

A systematic assessment of climate change impacts on mountain forest properties and the ES they provide was performed in the context of the ACQWA project. The focus was on five ES (carbon storage, runoff, timber production, diversity, and protection from natural hazards); four regionally downscaled climate scenarios that cover a wide range of possible future conditions were used; three complementary, state-of-the-art models of forest dynamics that were used to simulate a wide range of forest properties were employed; and the simulations in two climatically contrasting case study areas (catchments) of the European Alps at several spatial scales, from the stand to the entire catchment, were performed.

The results suggest that the sensitivity of mountain forest ES to a 2 °C warmer world depends heavily on the current climatic conditions of a region, the strong elevation gradients within a region, and the specific ES in question. The simulations project that large negative impacts will occur at low and intermediate elevations in dryer-warmer regions, where relatively small climatic shifts result in negative drought-related impacts on forest ES.

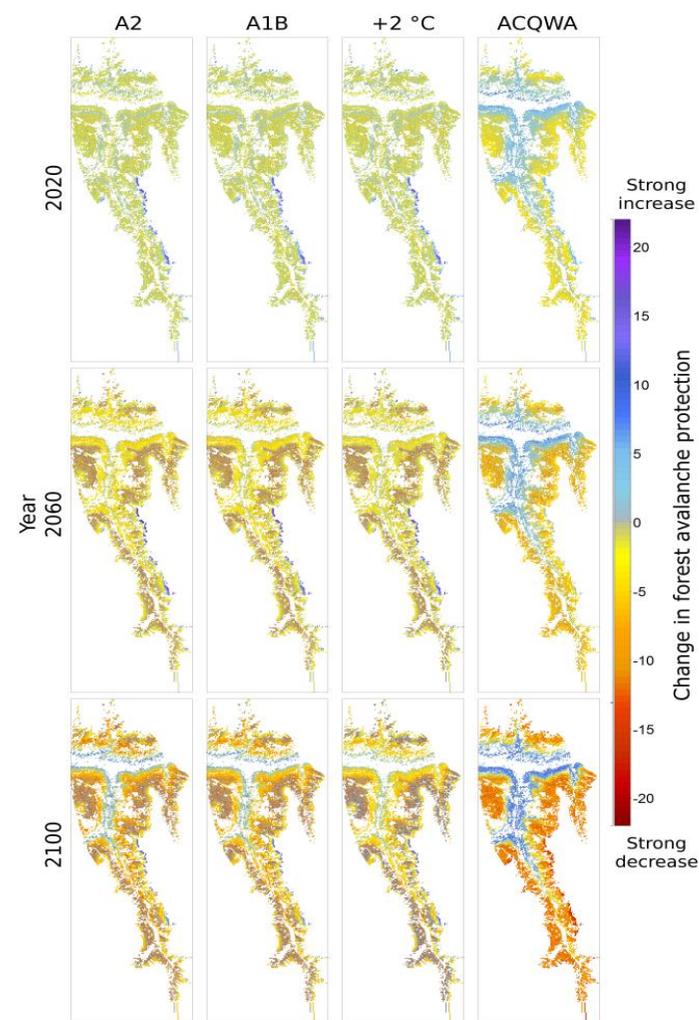


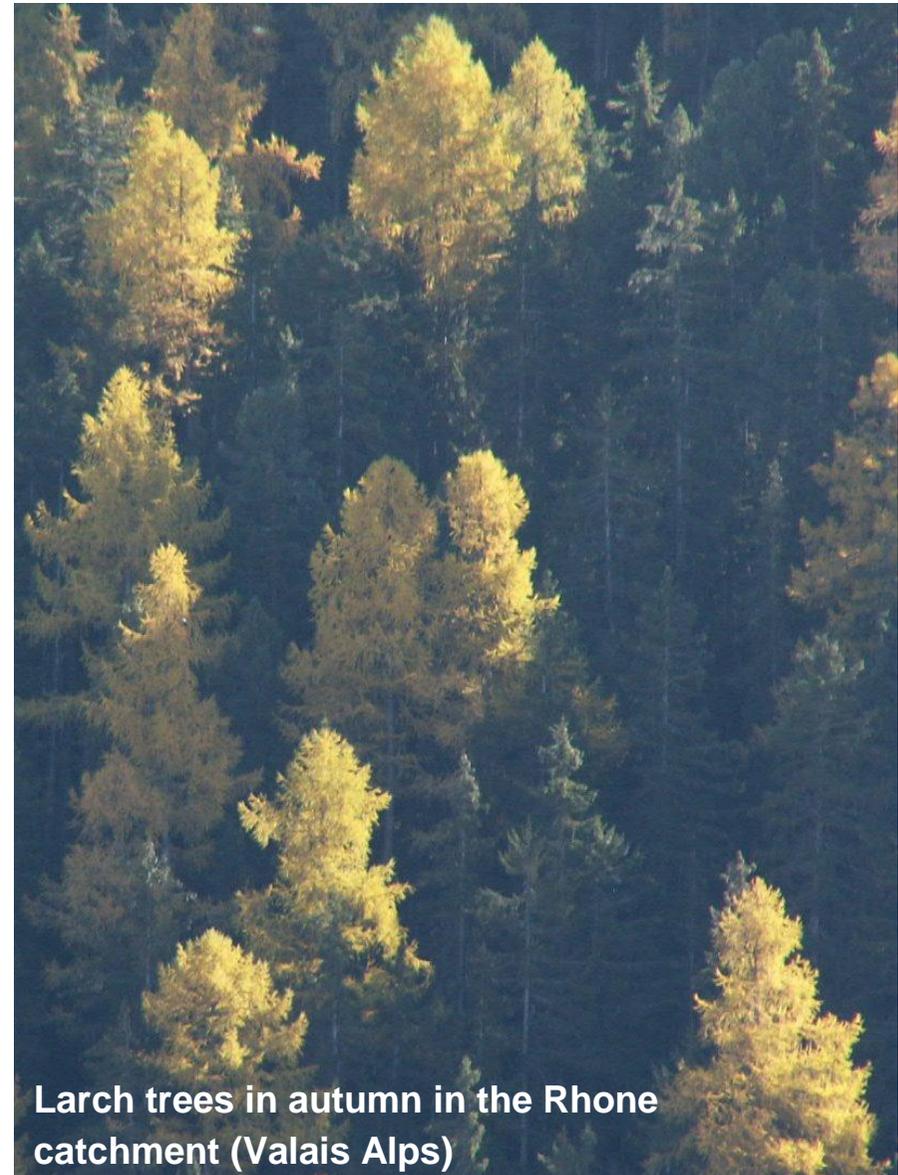
Figure 23: Changes in forest-derived avalanche protection in the Saas valley (part of the Rhone catchment) under four climate scenarios as projected using the forest landscape model LandClim. Changes are shown as normalized difference compared to 2010 levels.



In contrast, at higher elevations, and in regions that are initially cool-wet, our simulations suggest that forest ES will be comparatively resistant to a 2 °C warmer world. It was furthermore found that considerable variation exists in the vulnerability of forest ES to climate change, with some services such as protection against rock-fall and avalanches being sensitive to 2 °C global climate change, but other services such as carbon storage being reasonably resistant. While these results indicate a heterogeneous response of mountain forest ES to climate change, the projected substantial reduction of some forest ES in dry regions suggests that even a 2 °C increase of global mean temperature cannot be seen as a universally “safe” boundary for the maintenance of mountain forest ES.

Added value from the ACQWA project: The results achieved in the ACQWA context rely on research activities that were begun more than a decade ago and benefited considerably from the funding made available in ACQWA in the sense of a synthesis and further development of existing approaches. Beyond this, the added value of the project was the availability of state-of-the-art climate scenarios and the comprehensive focus of the study, as ACQWA has always emphasized cross-sectoral activities rather than isolated impact assessments of individual components of mountain systems.

Policy-relevance of this research. The high importance of mountain forest ES for human well-being both within and beyond mountain regions implies that the results from this part of ACQWA can inform the policy-making process and ecosystem management approaches, as follows. On the one hand, the high sensitivity and vulnerability of mountain ES as shown here suggest that climate mitigation strategies are of utmost importance. If greenhouse gas emissions continue at current levels (let alone if they increase), drastic and mostly negative impacts on mountain forest ES are to be expected. On the other hand, these results also provide pivotal information for ecosystem management by pinpointing regions and ES that are most likely to be particularly sensitive. This allows ecosystem managers to concentrate their efforts and to spend the limited financial resources in the most effective way.



Larch trees in autumn in the Rhone catchment (Valais Alps)



Impacts on tourism

SUMMARY OF KEY FINDINGS

- A more local approach to winter tourism exposure to climate change in the Rhone catchment (comparing across average winters, a snow-poor winter with average economic conditions and a snow-rich winter at the beginning of the current economic crisis) reveals high disparities between mountain resorts and a higher vulnerability than regional approaches have suggested.
- Although Valais witnessed a smaller reduction in skier days than other regions during snow-poor winters, some resorts were strongly affected, with a large disparity in the vulnerability of resorts (e.g., small and medium resorts).
- The hotel sector is less exposed to a snow-poor winter than the cable-car companies, but faces difficulties in some areas when longer trends and socio-economic factors are taken into account.
- There is a real need to increase cooperation among and within resorts and touristic regions, enhance coordination of water uses (e.g. , between hydro and cable-car companies), to improve the promotion of the Canton in general, to improve the ability to consider alternatives to skiing during warmer winters (notably in more vulnerable regions), and to improve current regulation on artificial snow-making.

The world-famous resort of Zermatt, in the Rhone catchment, at the foot of the Matterhorn (4,478 m)





Mountain tourism: the case of Valais, Switzerland

Overview: This part of the ACQWA project has investigated the climate-related and socio-economic drivers of winter tourism in the Swiss canton of Valais, as well as its expected water consumption in the future. Winter tourism is amongst the main economic sectors within the canton. The most significant finding is the industry's exposure to reduced snow cover. A report by the OECD published in 2007 depicted Valais as showing little vulnerability to the reduction of snowcover. However, instead of approaching the tourism industry at the cantonal level, a more regional/local approach of the canton (48 resorts grouped into 17 regions) has been adopted. By comparing two average winters (2004-06) with a snow-poor winter with average economic conditions (2006-07) and a snow-rich winter at the beginning of the current economic crisis (2008-09), the study reveals high disparities between the resorts. This is an indication that vulnerability assessments and, more particularly, adaptation measures should be considered at a much lower level than has been done so far.

Added value from the ACQWA project: Valais seems to be more exposed or vulnerable to climate change than previously expected. Although the canton witnessed a smaller reduction in skier days than other regions during snow-poor winters, some resorts were strongly affected. And just in removing the biggest resort of the canton (Zermatt) from the statistics, the impact of the exceptionally warm winter of 2005-06 appears to be much bigger: Instead of losing only 4.9% in the number of skiers, the canton would have lost 7.8%.

If the hotel sector proved less exposed to a snow-poor winter than the cable-car companies, the accommodation sector is facing serious difficulties in some regions when longer trends and socio-economic factors are taken into account. The canton could consider some support to the hotel sector so that they reach a "critical mass" of tourists, a strategy adopted by Austria, for instance.

Policy-relevance of this research: The study can be seen partly as a "wake-up call" in many respects. The main political implications of these findings are that policy-makers need to take into account the big disparity existing between regions, and how vulnerable small and medium size resorts can be to the changes that are expected to impact tourism in years to come. The main challenges are to find ways for increasing cooperation amongst and within resorts and touristic regions, improve the promotion of the canton in general (the label "Valais Excellence" and the website of "Valais Tourism" constitute a good start in this respect), and more vitally, the ability to consider alternatives to skiing during warmer winters, especially for more vulnerable regions

For the regions themselves, it would be advantageous to build further winter-sport infrastructure exclusively in snow-reliable regions (thus increasing their center of gravity) and to adopt a more integrated structure. The target – the type and origin of population they would like to attract for winter holidays – should be chosen carefully. More generally, stakeholders should be aware of potential changes in the tourists' preferences – a major unknown for the next decades. The future water consumption of the tourism industry can only be estimated. It can be said that the current coordination between the hydroelectric sector and the cable-car companies – in which the first sells water to the second for artificial snow-making purposes – should be maintained and perhaps even increased in some cases. More studies should be led to determine whether the current law on artificial snow in the canton should be improved in the future.

In addition, the type of tourists (according to: age, country of origin, and the social class) they expect to attract should be considered. The preference of a high social class can change within a small time frame, and it is uncertain whether the middle class would continue its skiing activities at the same level as it does currently, or even if it can afford this time of recreation in the future.

Lessons learned from non-European regions

SUMMARY OF KEY FINDINGS

- Illustrate challenges of climate change impacts in basins characterised by less robust institutions and lower levels of climate data.
- In the drier climates of Central Andes (Aconcagua and Cuyo basin) and central Asian (Syr Darya basin), glaciers and snow pack play a vital role in the natural storage of melt-water for release for irrigation purposes in the drier summer periods. In all three case areas, the combination of 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.
- Comparisons of water governance assessment across non-European and European basins underline the importance of enhancing institutional and actor trust in order to adapt to increased periods of summer drought in particular. Often, current reactive adaptations (e.g., increased [illegal and legal] groundwater exploitation, water transfers, water withholding) degrade the resilience of ecological systems as well as trust to build longer term, more proactive strategies to address climate impacts.
- Improved monitoring of ecosystem and water rights, accessible and available data integrated into decision making, integration of multiple knowledge sources, reinforcing and integrating user groups already in place, and more accessible, affordable and expedient conflict resolution mechanisms are recommended to enhance adaptive capacity.



Monitoring of the El Juncal Glacier in Chile

Overview: Ablation processes were studied during the ACQWA project on Glaciar Juncal Norte, central Chile, and high-altitude meteorological stations to monitor climate and precipitation in snow and ice-dominated basins were established in central (Juncal Norte) and Northern (Elqui Valley) Chile. Chile has traditionally been suffering from a paucity of continuous meteorological and hydrological data in snow and ice fed basins. These stations will be maintained to provide the data to the science community, and use it for ongoing research on the hydrology of snow and ice-fed basins. In addition, airborne surveys were conducted over the glaciers, as illustrated in Figure 25.

Added-value from the ACQWA project: The main added value is the installation of a permanent automatic weather station near Glaciar Juncal, which provides online data on precipitation, snow height and various meteorological parameters. Given the sustained drought conditions that have pertained in central-northern Chile since 2008, such data become invaluable for providing basic information about basin hydrology. A second precipitation gauge will be installed in the upper Elqui valley Basin, where drought conditions are now limiting crop growth. Data from this station will be used along previously collected data at Tapado glacier (Elqui) to drive a physical hydrological model of the basin such as done in central Chile.

Policy-relevance of this research: The severe drought conditions affecting central-northern Chile since 2008, has increased the need for authorities such as the Regional Government of the Coquimbo and Valparaiso Region, the Dirección General de Agua de Chile and the Junta de Vigilancia del Río Elqui to access more information on snow and ice water retention in the Andes. The ACQWA project has contributed toward this objective by providing new meteorological stations and new insights of snow and ice melt contribution to streamflow in central Chile.

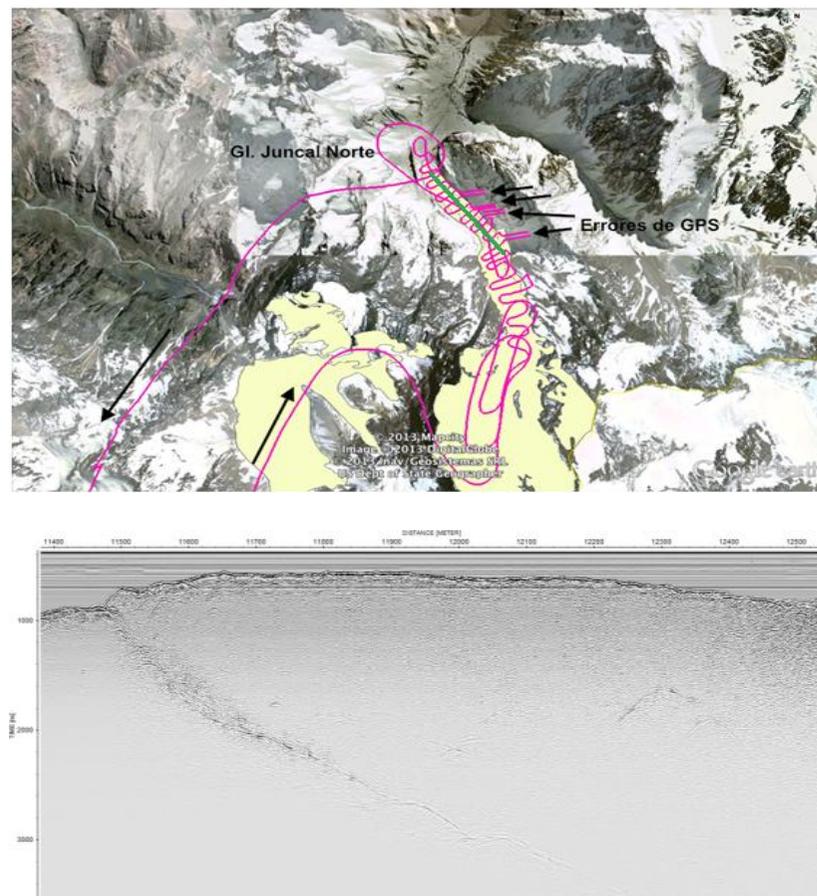


Figure 25. Upper: Helicopter borne radar survey tracks at Glaciar Juncal Norte measured in May 2013. Bottom: A radar profile (green line above) showing ice thickness down to 250 m.



The case of water governance in Chile

Chile represents a highly contrasting case to the European basins, from both a physical and a governance perspective. Water rights are a marketable commodity with minimal environmental regulation and no sectorial prioritization. Government institutions are highly centralized, with limited agency and capacity of water managers at the regional level. Increasing drought periods (from a combination of reduced summer runoff and altering precipitation patterns) are likely to compound current issues relating to the overuse of surface and groundwater from both legal and illegal abstractions in the Aconcagua Basin.

Major challenges from the governance perspective relate to the accuracy and applicability of monitoring data; lack of available, accurate, systematized and accessible information on water rights, water judgments, water market and prices, health and availability of water resources; climate data and uncertainty calculations are not used in planning; constricted agency and capacity of technical experts at the regional level; lack of trust and agreement on scientific studies and hydrological data that blocks consensus building; lack of a formal flexible conflict resolution mechanism.

A common thread across the different case studies are the challenges or opportunities presented by regional networks, actors and the differing levels of trust that can be capitalized for more integrated and longer term planning of water resources management. In the Aconcagua, there are a number of institutions that could be fostered to improve adaptive capacity. The Mesa del Agua is a collaborative attempt to strengthen inter-sectoral cooperation for the Aconcagua Project that should be made more inclusive with a broader, climate-related, goal orientation. While there is potential flexibility through the water rights system, denoting flexibility and autonomy to react quickly to changing conditions in the river, improvements to trust between river sections and more expedient and flexible conflict resolution mechanisms could greatly enhance its role in adaptation to drought conditions.



Headwaters of the Aconcagua river, Chile, shortly after it leaves the El Juncal Norte Glacier

Institutional environment and water governance in the Mendoza watershed in Cuyo, Argentina

Overview: During the ACQWA project, an analysis of the institutional environment in Argentina, its attributes and functionalities was undertaken, against the requirements to adequately respond to expected impacts on water resources and governance. Further, research focused on how the inherent constraints resulting from a dysfunctional institutional system have a potential to undermine adaptive capacity and adaptation actions to climate change. During the last three decades a weak institutional context created problems of credibility, coordination and cooperation and has had severe impacts on the quality of public policies. A weak institutional context is defined by low enforcement of the rules and/or by an application that is broadly discretionary and one in which institutional change is frequent and radical. Hence, Argentina's public policies tend to be unstable, poorly coordinated, weakly enforced, and highly rigid, and the decision making process lacks credibility. This persistent environment of instability, policy volatility, political short-termism and precarious enforcement pervades the water governance regime across scales and in the case study area, even in a formally highly decentralized federal system (as in other regions and sectors affected by the impacts of climate change). The decision making context, including drivers of water use, in a complex governance landscape, reinforces informational and cognitive, financial, social and cultural barriers to implement adaptation efforts and enhance adaptive capacities to improve the resilience of the social-ecological system. The scientific evidence that under projected climate change conditions the water resources of the Mendoza region could be reduced in a significant way thus requires the adoption of adaptive governance principles whose application is obstructed by rigidity, lack of cooperation and coordination, serial replacement (as opposed to predictable law and institutional structures) and fragmented or truncated learning processes and knowledge creation and dissemination.

Added value form the ACQWA project: Efforts to address inadequacy of governance components and mechanisms at the water resource management regime in Argentina, including knowledge and water resources planning and lack of appropriate incentives for conservation and efficient use of those resources, might be rendered sterile if they are limited to formally enunciate the application of integrated water resource management initiatives. The transformational potency of such efforts is limited given the persistent gap between planning and policies and measures and effective implementation, and the nature of the policy making processes in Argentina, where the interactions between the public sector and private agents are dominated by short-term considerations. The stasis of this structural condition was reinforced by recurrent macroeconomic crisis and external shocks. Hence, the prevailing insufficiency of inter-temporal governance capabilities, capacity for consensus building and emphasis in policy consistency. These traits impinge on the effective adoption of adaptive principles that should govern the conception and implementation of a resilience strategy.

Policy relevance of this research: Research has identified constraints – under an institutional approach – for embedding an adaptive strategy in a robust water governance regime, in the context of increased uncertainties and change and institutional frailties across scales. Further research is required aimed at identifying a possible range of solutions, in a non facilitative polity, leveraged on the enhanced scientific evidence base as a driver to institutional change and consensus building on the limited availability of choices under projected climate change far beyond the existing conditions.



Climate change impacts on Kyrgyzstan

Overview: Within the ACQWA project, the Syr Darya river basin in the Tien Shan ranges have been chosen as a pilot area for a specific case study. The goal is to illustrate the impact of climate change on a transboundary river, where complex responses result from asymmetric power relations and less robust institutions. Kyrgyzstan has the role of a water tower as many rivers – such as the Syr Darya – originate within the country's territory. The difficulty for the Central Asian states is to apply the principles of equitable use of water and to agree on a balanced reservoir management, which would allow the generation of energy in winter – benefiting upstream countries such as Kyrgyzstan – and irrigation for large-scale agriculture in summer – benefiting downstream countries such as Uzbekistan. Current challenges in the water operating regime are likely to be exacerbated by climate change impacts as water shortages during summer become more frequent with expected decreases in summer precipitation and reduced glacial meltwater releases due to smaller glacier volume.

Added value from the ACQWA project: The Tien Shan mountains are located in the center of the Eurasian continent; the distance to the nearest sea exceeds 1500 km. Arid and semi-arid climate conditions result from atmospheric flows coming from the Atlantic and the Arctic, which lose major parts of moisture over the European territories and Siberia. Research within the framework of the ACQWA project and based on previous studies under the UNFCCC have demonstrated that the most probable climate change scenario fits the emission scenario B2-MESSAGE. By 2050, Kyrgyzstan will thus experience an increase in average annual temperature by +2.5°C and an increase in annual precipitation sums by +2.5%, with increasing amounts in winter and decreasing amounts in summer. These climate changes have various impacts:

- In addition to the decreasing amounts of precipitation during summer, water shortages might be exacerbated by a decrease of glacial meltwater releases in the long-term due to reduced glacier volume. Glacier shrinkage is most

pronounced in peripheral, lower-elevation ranges near the densely populated forelands, where summers are dry and where snow and glacial meltwater is essential for water availability. Under the high greenhouse-gas emissions SRES A2 scenario, $31 \pm 4\%$ of today's glacier volume in the Syr Darya catchment may melt by 2050;

- Shifts of seasonal runoff maxima have already been observed in Kyrgyzstan, and summer runoff will probably further decrease if precipitation and discharge from thawing permafrost bodies do not compensate sufficiently for water shortfalls. Runoff may decrease by 15% (from the previous baseline year of 2000). Currently, however, river runoff in the formation zone of the Syr Darya basin is increasing due to intensive glacier melting. This trend is likely to continue up to 2025. After 2025, however, contribution of glaciers to river runoff in the headwaters of the Syr Darya will decrease irreversibly;
- Total hydropower potential of the Syr Darya basin may decrease by 14%;
- Heat supply for the vegetation period will increase by about 7% and the humidification index will be reduced by around 10%. Cumulative change in agro-climatic conditions will increase crop and pasture efficiency by 2-3%.

Policy-relevance of this research: Climate change as anticipated in the Syr Darya river basin calls for specific adaptation measures:

- Technical and infrastructural adaptation measures include a reconsideration of operating regimes as hydropower dams will need to replace glaciers as seasonal redistributors of water, and advanced water-saving techniques and practices as well as alternative, less water-consuming crops in irrigated agriculture.
- Governance-related adaptation measures include consistent data collection and dissemination; cross-sectoral collaboration; national responsibility and initiative; and agreeing on a regional strategy.

Given the interconnected nature of the hydrological system in the Syr Darya river basin, as well as the Soviet legacy in the definition of a common water management paradigm, institutions can only become and remain adaptive if a mutually-agreed and shared regional strategy is in place.



PART 4

POLICY, ADAPTATION, GOVERNANCE

Policy analysis and adaptation options

SUMMARY OF KEY FINDINGS

- In the Po basin, despite the farmers' observed investments to adapt to mean changes in climate at local level, unanticipated variability in climate continues to impact crop yields. Policy interventions (integration or water resources, water storage) must therefore deal with residual uncertainty remaining after local adaptation to climate change.
- In the Upper Rhone basin, the increasing heterogeneity of precipitation and late summer reductions in run-off from reduced glacier melt are likely to further exacerbate current local critical situations, bottleneck periods for local water supply, which are themselves related to: high levels of autonomy at municipal level that block longer term catchment scale planning and smoothing of bottleneck periods; lack of formal mechanisms to manage competition across catchment areas; lack of rules on emerging challenges and uses.
- Earlier snow melt and shifting glacier melt patterns are likely to impact the inflexible and long term user rights that govern uses such as hydropower 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.
- In response to climate change impacts as well as the continuing challenges concerning uncertainty, adaptation strategies are recommended that are no-regret, flexible and iterative, that allow for safety margins and redundancy in new investments, take a long term and social and green infrastructural approach (to complement grey infrastructure), and that integrate both adaptation and mitigation requirements.

Economic modelling of water resource management for climate adaptation

Overview: For part of the ACQWA policy analysis, the implications for management and decision making within a sequential decision making environment have been modelled, where risk and uncertainty are expected to be significant factors. A simple dynamic optimization model has been used to illustrate the potential for suboptimal management of the quantity and spatial allocation of water resources.

Added value from the ACQWA project: The basic dynamic optimization model has been extended by including heterogeneous costs in accessing the water resources (e.g. heterogeneous pumping costs), which is the main contribution of this part of the ACQWA-sponsored research to the existing literature. By doing so, it is shown that heterogeneity in access to the water resource may be a significant source of externalities, which further complicates the work of the water manager and it may require government intervention.

The manner in which decentralized decision making and heterogeneous costs in accessing the water resource imply a water storage problem has been analyzed. This is even more relevant with increasing variability of precipitation over time. A scenario has been analyzed, where the lack of water management planning (i.e., unrestricted or poorly managed access to the water stocks) leads to negative externalities and unwanted fluctuation in agricultural yields and hence income. In particular, farmers in areas characterized by more expensive access to the water

stock resources will be heavily penalized by the lack of water management policies.

Policy-relevance of this research: If managed efficiently, water storage can be used as a tool to smooth variability in climatic variables. The specific case study of the Po river basin has been analyzed in this context. This area is characterized by heterogeneous topographical features and intensive water use in agriculture (Figure 24).

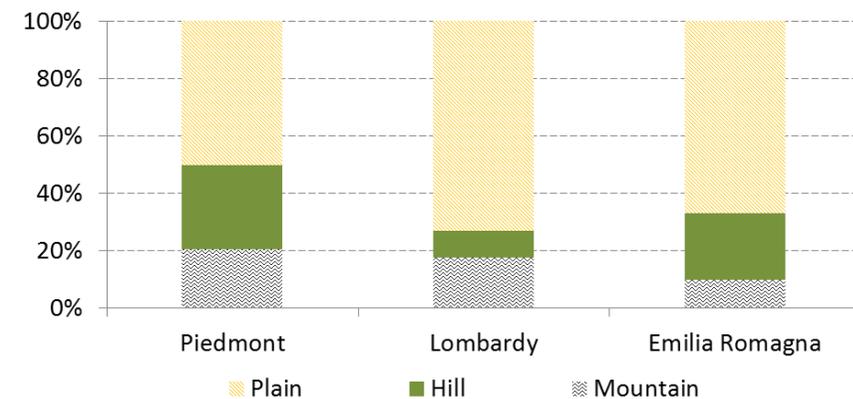


Figure 24: Topographic features of the usable agricultural land, by region. Source: own elaboration on data ISTAT (Agricultural Census, 2010).

Recent drought periods, along with increasing pressure by growing population and economic activities, have served to highlight the role played by water resources stocks in dealing with fluctuations of surface water supply. Groundwater, farm ponds, water in dams and lakes, or other forms of water stocks can be used to smooth the increasing volatility in surface water supply, triggered by higher rainfall variability.



Options for adaptive capacity, policy and governance recommendations for each basin

In the case of the Upper Rhône basin, existing spatial and temporal challenges in the governance and management of water are likely to be compounded by climate change impacts. For example increasing heterogeneity of precipitation as well as late summer reductions in run-off from reduced glacier melt are likely to further exacerbate current local critical situations, bottleneck periods for local water supply, which are themselves related to: high levels of

autonomy at municipal level that block longer term catchment scale planning and smoothing of bottleneck periods; lack of formal mechanisms to manage competition across catchment areas; lack of rules on emerging challenges and uses. Earlier snow melt and shifting glacier melt patterns are likely to impact the inflexible and long term user rights that govern uses such as hydropower 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.

In order to respond to both underlying and climate related governance challenges, it is recommended that policy makers focus on the integration of information and development of knowledge through iterative, flexible, collaborative and connective approaches to increase adaptive capacity and support the sustainability of water systems.

Adaptive Governance Principles	Actionable Governance Mechanisms [Policy, Legislation, Regulation, Property Rights]
Iterativity	Time-bound review periods with potential reallocations. Varied rights (subject to ecological and social parameters) & Permit systems. Administrative requirements in separate secondary legislation. Review periods for fixed term rights (subject to social and ecological obligations).
Flexibility	Time limited licencing so regulators can vary use rights in advance of expected changes. Use entitlements as share of overall resource (planning framework addresses situation in 50 years). Emergency provisions and powers during drought and flood events. Administrative requirements for qualitative & quantitative standards. Risk apportionment across variety of actors Variable use rights in anticipation of changing conditions (subject to social and ecological obligations)
Connectivity	Integrated water use licencing & tiered water use licencing. Monitoring Standards for available and accessible data (publicly available & data exchange). Consultation Process (river basin management planning process is bound by detailed stakeholder review mechanisms and coordination between sectoral management authorities). Requirements for exchange of data.
Subsidiarity	Locally Appropriate Standards (broad principles based in primary legislation and implementation of principles set out in secondary legislation). Administrative requirements for setting basin specific standards. Implementation of use rights frameworks at lowest appropriate level.

Table 3: Specific and actionable governance mechanism for applying adaptive governance principles and balance flexibility of adaptation with requisite predictability of legal structures



Finalised adaptive capacity, policy and governance recommendations for each basin

In response to climate change impacts as well as the continuing challenges concerning uncertainty, adaptation strategies are recommended that are no-regret, flexible and iterative, that allow for safety margins and redundancy in new investments, take a long term and soft approach (rather than just hard infrastructure), and that integrate both adaptation and mitigation requirements. As adaptation policy and projects are operationalized, future work should

continue to monitor the implementation of these measures to ensure that new information is integrated, trade-offs are limited across governance scales and sectors, and any negative feedbacks halted. Shifting the adaptation focus from single sector and hard infrastructural projects to multi-benefit cross-sector approaches is more likely to lead to increasingly transformational approaches to adaptation that can enhance the resilience of these basins to increasing levels of uncertainty and multiple stresses in the hydro-climatic system, rather than adaptation that might degrade resilience.

Scale	Actionable Measures and Governance Mechanisms	
	Policy & Law	Management & Actors
Local – Regional	<ul style="list-style-type: none"> -Integrated assessment of development & adaptation: evaluate possible conflicts and synergies (e.g., agricultural development, habitat conservation, energy security and ecosystem service provision). -Establish periods of review for provisions concerning existing concession provisions or calculation bases for residual flows as discharge patterns are modified. -Establish rules and procedures at appropriate level for water distribution during bottleneck periods and periods of water shortage e.g. enhanced demand management to reduce both surface and groundwater abstractions; time limited licensing, local and periodic restrictions, compensation schemes, water recycling. 	<ul style="list-style-type: none"> - Improve inter-linkages of local supply network of water and wastewater utilities. -Preparation of civil protection forces for increased flooding, forest fires, etc. -Modification /updating of hazard plans – inclusion of new and emerging hazards. -Restoration of riparian habitats: recreation of riparian buffer zones, wetlands and active floodplains (potential demonstration sites). -Monitoring & Observation: Integration of multiple knowledge sources; accessible & available data integrated into decision making; Adaptation of reservoir management & hydroelectric power generation to changing flow rates and regimes as snow and ice patterns change. -Diversify tourism adaptation so it is less dependent on snow-making post 2050. -Promote best agricultural practice for land and water management (increasing water retention and storage capacities of soils, selecting suitable plant breeds and optimizing irrigation systems). -Re-orientation of water management at regional rather than local level; diversification & optimization of water reserves, reservoirs & lakes for effective basin or catchment management. -Bring land and water managers together for integrated catchment area management.
Regional - National	<ul style="list-style-type: none"> -Monitoring & observation – extend application of data; integration of climate projections. - Establish common principles for management of water bodies and resources across energy, tourism, domestic and ecological requirements. - Regional adaptation planning that takes into account conflicts and synergies between strategies. - Provide legal basis for disaster funds, financial assessments & financing of ecosystem based & technical hazard prevention. 	<ul style="list-style-type: none"> -Collaborative networks for the integrated assessment of development & adaptation: evaluate possible conflicts and synergies (e.g., agricultural development, habitat conservation, energy security and ecosystem service provision). -Development of multipurpose use of reservoirs and lake regulation to enhance redundancy in the system. -Formalization of current regional networks for water management.

Table 4:: Adaptation Priorities for adapting sustainably to both uncertainties from climate variability and climate change.



Aerial view of the Chilean Andes, between
Santiago de Chile and La Serena

PART 5

CLOSING PAGES

Challenges for future research

Large integrating projects generally represent a step forward in furthering our understanding of various complex processes and interactions between environmental, economic, social, and technological systems. The ACQWA project is no exception to this rule, and the five years of research has indeed enabled a number of issues to be refined and clarified, but has also identified problem areas that would need to be addressed in future investigations of this nature.

In January 2011, the ACQWA project organized a workshop in Riederalp, Switzerland, where over 25 EU projects focusing on water resources and water management were represented. Institutional and financial obstacles to data access for use in modeling exercises were identified, and gaps in scientific knowledge that contribute to uncertainty were highlighted. A working paper was subsequently published in 2012 in *Environmental Science and Policy*¹ to report on the main conclusions of this crucial meeting. The discussions summarized in the paper have identified a number of sectors where these gaps often represent barriers to successful research outcomes, and suggested ways and means of alleviating some of these difficulties. A major issue that has been raised is that of data for research purposes. Policies aimed at ensuring free and unrestricted access to data, especially those generated by the numerous research projects that focus on issues of water availability, quality and management have been recommended. Implementation of the recommendations formulated in the *Environmental Science and Policy* paper may help pave the way for a more rapid and efficient production of research results that are of importance for policy guidance at the local, national and supra-national (EU) levels.

There is a clear need for a **more integrated and comprehensive approach to water use and management**. In particular, beyond the conventional water basin management perspective, there is a **need to consider other socio-economic factors and the manner in which water policies interact with, or are affected by, other policies at the local, national, and supra-national levels**. As an

example, **it is unclear whether current EU water policies are consistent with energy, agriculture, and other industrial policies**.

The problems highlighted during the Riederalp meeting and summarized in the cited paper are also related to the **inconsistencies between physical and socio-economic data and models**. For example, figures related to water use may not be available at the temporal and spatial detail required by hydrologic models. Hydrological information is often based on basins whereas economic (and social) data is aggregated into administration regions. Thus, economic and physical data are often incompatible, because they are collected by different entities for different purposes. **Future research should thus address the development of compatible data sets and the conversion between different data formats**, as well as the development of toolboxes for up-scaling, downscaling and bias correcting data. Furthermore, the use of water in production processes is often not mediated by the market. **The use of economic flexibility mechanisms in the allocation of water resources is quite rare**, despite their potential in improving the efficiency of water resources allocation. **More research and policy initiatives in this direction are thus necessary**.

Finally, many scientists working in large integrated projects highlight a large **gap between Science and Policy**. This is certainly at least partly due to problems of **communicating in an appropriate manner the key research results that would be of use to policy-relevant strategies**. Awareness of this problem is increasing within the EC and other policy institutions, and hopefully this new momentum will be sustained over time so that conclusions from EU and other water-relevant projects will be widely incorporated into future policies at the local, national, and supra-national levels. Ultimately, the **implementation of guidelines, maybe even an EU Directive, on the good governance of data** (sharing) could be envisaged as a possible framework, providing advice and general rules on data formats and standards, data storage after project completion or the general terms of access.

1: Beniston, M., Stoffel, M., Harding, R., Kernan, M., Ludwig, R., Moors, E., Samuels, P., Tockner, K., 2012: Obstacles to data access for research related to climate and water: implications for science and EU policy-making. *Environmental Science and Policy*, 17, 41-48.

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