Alpine Aquatic Ecosystem Conservation Policy in a Changing Climate

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Abstract

Freshwater ecosystems are often of high conservation value, yet many have been degraded significantly by direct anthropogenic impacts and are further threatened by global environmental change. Traditionally, conservation science and policy has promoted principles based on preservation and restoration paradigms, which are linked to assumptions of stationarity and uniformitarianism. Adaptation requires new approaches based on flexibility, iterativity, non-linearity, and redundancy. Many high alpine river networks represent near natural, pristine river systems and important biodiversity 'hotspots' of European freshwater fauna. However, there remains a lack of guidance on alpine river conservation strategies under a changing climate at EU, regional and local levels. A critical evaluation of current conservation and adaptation principles and governance frameworks was undertaken with relation to predicted climate change impacts on freshwater ecosystems. Case studies are presented from two alpine zones in mainland Europe (the Pyrénées and the Swiss Alps). The complexity of climate change impacts on hydrological regimes, habitat and biota from both case study regions suggests that current legislative and policy mechanisms, which frame conservation approaches, need to be realigned. In particular, a shift in focus from species-centric approaches to more holistic ecosystem functioning conservation is proposed. A methodological approach is set out that may help conservationists and resource managers to both prioritise their efforts, and better predict future habitat and biotic responses to set ecological baseline conditions. Due to the complexity and limited potential for preventative intervention in these systems, conservation strategies should focus on: (i) the maintenance and enhancement of connectivity within and between alpine river basins and (ii) the control and reduction of additional anthropogenic stressors.

1. Introduction

The physicochemical template of freshwater ecosystems is highly diverse, both between (e.g. wetlands, rivers, lakes) and within biotypes (Brown et al., 2003), supporting habitats and species of high conservation value (Wilcox and Thurow, 2006). However, many of these systems, particularly in lowland or populated areas, have been significantly degraded by global environmental change and direct anthropogenic impacts such as urbanisation, regulation, channelisation, pollutants and non-native species invasions (Dudgeon et al., 2006; Mainstone, 2008). In response to these continued impacts, conservation science and policy have promoted principles based on preservation and restoration paradigms, assuming ecological change to be both predictable and reversible (Craig, 2009). As a result, freshwater conservation efforts during the late 20th century have focused on (1) protection, through the designation of parks, priority habitats and listed species; and (2) reduction of certain types of pollutants, particularly organic and acidic precursors.

In the 21st century, many environmental scholars are questioning whether the current emphasis of conservation approaches towards environmental protection in static reserves and restoring or retaining the naturalness of the landscape (Callicott et al., 2000; Muir et al, 2012), is adequate for tackling increased uncertainty from complex climate related challenges (Milly et al., 2008; Shellenberger and Nordhaus, 2004). Moreover, major changes in state, rather than pollutant impacts, are likely to lie beyond social and ecological coping ranges (Yohe and Tol, 2002; Smit and Wandel, 2006). These challenges need to be understood better by conservation science and better addressed by conservation adaptation. This is particularly the case for alpine river systems, which not only represent important biological repositories of European freshwater fauna (Brown et al., 2009; Tierno de Figueroa et al., 2010), but are also highly exposed and sensitive to impacts from climate change (Beniston, 2005). Despite alarming predictions regarding extinction threats (Tierno de Figueroa et al., 2010; Muhlfeld et al., 2011), approaches to conserve this unique alpine fauna remain poorly understood (Brown et al., 2009).

Alpine river ecosystems are highly sensitive to climatic forcing (Hannah et al. 2007) and represent 'sentinel systems' (Füreder et al. 2002) which, given sufficient levels of monitoring, hold the potential to provide early signals of climate-induced ecosystem shifts (Grabherr et al., 2000). Alpine river basin conservation strategies should be developed using a framework that incorporates the cascade of environmental processes (climate – hydrology - habitat), which ultimately, determine biotic communities (Hannah et al., 2007). However, it is also important to consider biogeographical and geomorphological variability (Weekes et al., 2012), particularly as the separation of the climate signal from other environmental variables is necessary to attribute drivers of detected changes.

This paper is based on research from the EU-FP7consortium ACQWA (Assessing Climatic change and impacts on the Quantity and quality of Water in mountain regions; www.acqwa.ch). The ACQWA project takes an interdisciplinary and holistic approach to assess the physical, environmental and socio-economic responses to climate induced changes in water resources (Beniston, 2012). Specifically, this article assesses the aptness of current conservation and adaptation principles in alpine freshwater ecosystems in the context of climate change. Case studies are presented from two alpine zones in mainland Europe, namely the Pyrénées (limited glacial ice cover) and the Alps (highly glacierized). First, current conservation and adaptation principles are reviewed, followed by an analysis of the policy and legislation that frames these principles. Thereafter, an overview is given of the impacts of climate change on freshwater ecosystems to inform assessment of the suitability of current principles, actions and legal provisions for ecosystem management and conservation to the observed and projected impacts on alpine freshwater ecosystems.

2. Principles in Conservation Policy and Adaptation

Despite a growing body of work on adaptation principles for conservation and ecosystem management, it has been recognised that there remains a paucity of operationalised measures with the specificity needed for policy makers and conservation managers to implement (Clarke, 2009; Wilby et al, 2010, Heller and Zavaleta, 2009) particularly with respect the conservation of alpine aquatic systems. Herein the existing principles for conservation and emerging adaptation principles (see Table 1) for conservation are reviewed (for comprehensive reviews of adaptation conservation principles see Heller and Zavaleta, 2009; Muir et al., 2012; Wilby et al., 2010).

2.1. Conservation Policy

Although extinction rates in freshwater environments are significantly higher than in terrestrial systems (Abell, 2002; Strayer and Dudgeon, 2010; Tockner et al., 2011), conservation research and practice for freshwater systems has lagged behind that of other ecosystems (Linke et al., 2011). Conservation planning is made more difficult by the embedded nature of the river system within the terrestrial matrix (Woodward et al., 2010). Hence, land cover type (e.g. agricultural, impervious surfaces or glacier ice) has direct implications for in-stream biodiversity and ecosystem function. Linke et al.(2011) advocated the use of CARE principles in freshwater conservation planning (see Box 1), and highlighted the need for carefully selected biodiversity surrogates and adequacy targets during the planning stages. Active stakeholder involvement is also key when implementing conservation plans, particularly to ensure connectivity is maintained and the intervening matrix is not degraded (Linke et al., 2011; Rivers-Moore et al., 2011). However, the principles outlined above fail to provide an adequate or coherent framework to deliver conservation measures in the context of climate change.

2.2. Adaptation Principles for Conservation

To cope more effectively with, and adapt to, increasingly uncertain conditions, a growing body of principles is intended to help guide conservation in a changing climate. Managers of parks and protected areas or freshwater bodies are seen to face choices in adapting reactively or proactively, in building in resistance or resilience to changing conditions, and in balancing adaptation with other priorities (Palmer et al., 2009; Wilby et al, 2010). To meet these challenges, scholars have recommended developing robust adaptation measures that are '*low regret, or reversible, incorporate safety margins, employ 'soft' solutions, are flexible and mindful of actions being taken by others to either mitigate or adapt to climate change'* (Hallegatte, 2009).

In light of predicted climate change and these adaptation priorities, a generic first level framework for prioritising landscapes for management intervention has been advocated (Gillson et al., 2013). This approach is based on two 'axes of concern' (i) landscape conservation capacity, and (ii) vulnerability to climate change (Dawson et al., 2011; Gillson et al., 2013). The conservation capacity of a given landscape is defined by the amount of protected area, connectivity and matrix condition. However, the use of protected area must be carefully considered as these can be of multiple 'types' (see IUCN I-VI guidelines for example). In particular some protected areas were designated with the aim of increasing human use, which in a fragile environment could well be a destructive threat. However, in an alpine context where most protected areas are designated national parks it makes the implementation of conservation measures a simpler process due to the involvement of fewer stakeholders/ landowners. Landscape vulnerability and sensitivity relates to the altitudinal range (i.e. do species have room to track climate niche shifts), the abiotic diversity covered and susceptibility to climate change (Fig. 1). We propose that this approach offers an intuitive framework for developing alpine river system conservation plans. Particularly, due to the high spatial variability and sensitivity to climate fluctuations which necessitate a rapid assessment tool for identification of priority habitats.

3. Legislation and Policy Principles underpinning Freshwater Conservation Approaches

In light of climate change impacts, legal requirements may need to move from prioritising resistance to the resilience of ecosystems (Wilby et al., 2010), although it should be added that these different strategies are not mutually exclusive (Heller and Zavaleta, 2009). Prioritising certain species or community assemblages may limit adaptation to cross-scale challenges (Garmestani and Benson, 2010). Furthermore, changing baselines (increasing temperatures and changing flow regimes) are likely to undermine such targets (Clarke, 2009). Key policy and legislative provisions that frame freshwater conservation in the two case areas are summarized in Table 2. While the scope of the paper does not allow for a detailed review of all the levels and sources of law (see supplementary materials for full listing of laws reviewed), this section provides an overview of the type of conservation approaches the key provisions are prioritising by characterising the goals and priorities according to the paradigms identified in sections 1 and 2 (i.e. preservation, restoration, prevention in a static environment versus dynamic cross-scale complex adaptation).

While some articles and objectives outlined above for both case areas are moving beyond preservationist principles and assumptions of stationarity (Ruhl, 1997), the majority tend to focus on the restoration and preservation of a 'natural state'. In most cases these are defined by set species, with reference to specific functions limited to a small subset of current legislation (i.e. river-flood plain connectivity; EC 2009a). Habitat protection strategies in both cases prioritise the maintenance of stable species, their structure and function, that are '*representative of historically-defined communities for a given biome or ecosystem'* (Wilby et al, 2010, p4159).There is also a greater focus on the water body itself, rather than on activities and processes in the wider landscape, which influences in-stream physicochemical characteristics (Mainstone and Clarke, 2008) and on which climate change may have an intensifying influence (Lane et al., 2007).

The provisions and objectives of the EU Water Framework Directive (WFD) and Habitats Directive affecting freshwater ecosystems have been proposed as being sensitive and adaptable to climate change impacts (EEA, 2007; Mainstone, 2008; Wilby et al., 2006). However, Clarke (2009) views them as being based on static definitions of habitat and historic reference conditions. As point source or diffuse pollutants are still the major focus, the WFD objectives do not explicitly accommodate changing baseline conditions in relation to indirect anthropogenic influences from climate change, (Callicott et al., 2000; Muir et al., 2012). However, the role of the WFD second-round River Basin Management Plans (RBMP) have been emphasised as potentially providing opportunities to integrate climate change adaptation simply through its iterative 6 year review process, thus providing a timely window of opportunity to explicitly consider climate change by increasing knowledge of potential climate risks for individual river basins, strengthening data collection and knowledge exchange amongst key stakeholders, integrating and partnering across sectors, as well as raising awareness, education and training (EC, 2009b).

While underpinning rationale and processes of the WFD (i.e. its integrated approach to land, water and ecosystem management, combined with the cyclical review process) is seen as amenable to climate change adaptation (or more specifically adaptive management approaches), the general principles provided within the climate guidance not only retain a focus on restoration and the reduction of broad stressors but also have a paucity of specificity (EC, 2009b). Therefore in both cases, the emerging policy guidance for climate change adaptation in water resources and habitat legislation and policy has been less specific on clear actionable measures, especially in the context of alpine environments. Furthermore, they have not been mainstreamed into water manager's toolkits (Brouwer et al., 2012) nor fully integrated into current legislative frameworks.

4. Climate Change Impacts on Freshwater Ecosystems in the French Pyrénées and Swiss Alps

4.1 Study areas

Two test river basins (Fig. 2) were selected for comparison due to distinct differences in glacier cover and downstream influence and the proportion of the basin protected. The Taillon - Gabiétous basin, Cirque de Gavarnie, French Pyrénées (43°6'N, 0°10'W) represents the southern limit of contemporary European glaciation (Hannah et al., 2000). Here, two small remnant cirque glaciers (Table 3) are located on north facing slopes shaded heavily by the surrounding peaks and cirque walls. These two glaciers are representative of the remaining 21 glacier in the Pyrénées, all of which are small (<0.5km) (Grunewald and Scheithauer, 2010). Rates of retreat have been significant over the last decade (Taillon: - 79m ; Gabiétous: -21m; Association Moraine 2009). Hannah et al. (2007) highlight the species specific focus of conservation strategies within the Parc National des Pyrénées with a distinct bias towards larger, enigmatic terrestrial fauna. In contrast the upper Rhone basin or 'Gletschbode', Swiss Alps (46°33'N, 8°24'W) is significantly larger (Table 3) with two glaciers, the Rhonegletscher, a medium sized valley glacier, and the Muttgletscher a smaller mountain glacier. Both have receded over the last decade (Rhone: -110m; Mutt:-120m; Rapport glaciologique1881-2009).The vegetation on the shallow slopes of both these basins is comprised of scrub (*Alnus, Salix*) and grazed alpine meadow. Given the prominent importance of hydropower production in Switzerland, the rate of glacier loss is of major concern as it affects glacier-fed running waters and the water cycle in general on various spatial and temporal scales (Romerio, 2008; Gobiet et al., in press).

Due to less glacier ice cover in the Pyrenean basins, compared to those in European Alps, discharge regime magnitude and variability are markedly different at seasonal, sub-seasonal and daily time scales. The hydrograph for the Taillon basin displays a distinct snow melt peak in June and a gradual decline during July and August as snowpack volume reduces and ice melt contributes (Fig. 3a). In contrast, the hydrograph for the upper Rhone has a distinct snowmelt peak in June but discharge during July and August remains high, although diurnal variability increases, as melting glacier ice is the main flow source (Fig. 3b). These two flow regimes represents different locations along a continuum of glacier loss; the Taillon basin has limited annual flow regime compensation by glacier melt cycles following substantial loss of ice cover and (scenario C: Fig. 3c & d), for the upper Rhone basin although there has been loss of ice cover, significant mass remains for glacier melt to generate summer high flows (scenario A/B: Fig. 3c & d).

4.2 Methodology

To assess the impact of projected climate change on river basin ecology, statistical models were employed to relate aquatic benthic invertebrate occurrence and key environmental variables. Benthic macroinvertebrates in alpine river systems are well studied and are ubiquitous due to broad environmental tolerance ranges, thus were chosen as a 'model' group (Jacobsen et al., 2012). In both basins replicate Surber samples were collected across a gradient of glacial influence during the summer melt season. Taxa were identified to the lowest practical taxonomic level (usually species or genera). Contemporary relationships between benthic biodiversity and glacial influence (see, Knispel and Castella, 2003; Brown et al., 2007) were then used to inform our future predictions. A range of, hydrological and cryospheric variables were derived from a dynamic catchment hydrological model

(TOPKAPI; Ciarapica and Todini, 2002), which has been significantly modified for use in mountainous environments (Finger et al., 2011). TOPKAPI was fed with downscaled climate scenarios (RCM:REMO) for the 2050 horizon (Fig. 4),climate scenarios were carried out as part of the EU-FP6 ENSEBLES project, using the global ECHAM5 A1B scenario for driving boundary conditions (van der Linden and Mitchell 2009). Model outputs enabled identification of key changes in the hydrological regimes and in-stream physicochemical habitat. As benthic assemblages in high headwater alpine streams appear strongly deterministic, especially in highly glacial reaches where environmental filtering is particularly strong (Castella et al., 2001), habitat template changes can be used to predict how biodiversity and ecosystem functioning will respond (Fig.4). Changes in glacier cover/meltwater contribution can be used as a surrogate for the suite of environmental parameters which dictate macroinvertebrate community structure (Milner et al., 2009).

4.3. Results

Future climate scenarios (2050 horizon) are broadly similar for the two study regions predicting increased air temperature and decreased summer precipitation (Table 4). Winter precipitation is expected to increase for the Taillon, although the snow:rain ratio will decrease. In contrast, the Rhone snow:rain ratio is predicted to increase (Fig. 5). For the Taillon basin, the future hydrological regime will become more pluvial with reduced total magnitude with no compensation flows from melting ice predicted by 2050. Interestingly, for the upper Rhone while total discharge magnitude is expected to decrease, the hydrological regime is different for the two sub-basins (Fig. 5), as glacier flow compensation is likely to increase for the Rhone sub-catchment but decrease for the Mutt sub-catchment that has a reduced glacierized area.

Similarities are apparent between the Taillon and Mutt river systems with respect to benthic habitat and biotic communities. At previously glacier dominated 'harsh' (low channel stability, water clarity and water temperature) sites, the physicochemical habitat template is expected to become more 'benign' (high channel stability, water clarity and water temperature) and alpha (local) diversity is expected to increase. Glacier specialist taxa are expected to disappear from the Mutt and Taillon basins, which in the case of the Taillon will lead to a reduction in gamma (regional) diversity. For the Rhone, local diversity is expected to be maintained or even decrease as increased ice melt contribution to flow creates more disturbed in-stream habitats with higher water turbidity and colder temperature. However, when considering the Rhone basin, an increase in regional diversity is expected in the short term due to between sub-catchment variability in hydrological and habitat responses (e.g. habitat heterogeneity increased).

5. Discussion

The results of climate change impacts on the two alpine case studies indicate that current conservation legislation and policy for aquatic systems needs to reconsider the baseline conditions and conservation goals to better enable managers to be responsive to future stresses. This is particularly poignant when considering alpine river ecosystems, which are highly sensitive to climatic forcing yet currently provide a number of important ‘services’ (Brauman et al., 2007). These fall into three broad categories each providing distinct ecosystem services: (i) predictable water storage and release which represents both a provisioning and cultural ecosystem service, (see de Groot et al., 2010),by facilitating socio-economic needs, including, water resource provision, hydro-power production, agriculture (irrigation) and tourism (Beniston, 2012); (ii) nutrient retention and uptake (a regulating ecosystem service); (iii) serving as repositories of biodiversity and unique genetic material (a supporting ecosystem service). The potential conflicts of interest between the numerous stakeholders (e.g. farmers, environmental groups, tourists, and hydropower companies), which have vested interests in different ‘services’, makes the task of adaptive conservation in alpine environments both difficult and important.

5.1. Shifting Priorities: Conservation and Adaptation in the Alpine Context.

In alpine river systems climatic warming will alter the strong linkages between climate-hydrology-habitat-ecology (see Fig. 5) and, thus, has implications for biodiversity in alpine streams (Finn et al., 2013). More specifically, the loss of a number of endemic, glacier stream specialists is likely to occur (Brown et al., 2007), particularly in basins fed by small glaciers such as the Taillon and the Mutt. This will lead to a reduction in basin and regional scale diversity (Jacobsen et al., 2012) despite a predicted increase in alpha (site) diversity as water source contributions change (Milner et al., 2009). This highlights the need for careful consideration regarding how biodiversity is measured and interpreted in the context of conservation, particularly in alpine environments where between site diversity and range restricted, endemic taxa are important components of regional biodiversity.

The complexity of these impacts, and limited range of viable preventative intervention measures (e.g. cold water discharges or habitat alteration), support the case for a shift in conservation from a species centric focus to a more holistic approach. This would consider ecosystem functioning rather than preservation of baseline species and community structures as the prime facet of conservation interest. Section 4 details the aspects of policy guidance and Table 2 details the set of provisions that are attempting to promote the enhancement of ecological re-naturalisation and (in the case of the WFD) the introduction of more iterative planning approaches (i.e. cyclical planning approach) to improve resilience to climate change impacts. However, these provisions and goals remain couched within broader aims to preserve and restore key species and priority habitats to baseline conditions.

Within the legislative frameworks of each case, provisions to 'maintain and restore natural habitats and species' through 'parks, protected areas and reserves' (see Table 2), could better account for the growing need to address multiple threats and global change drivers (Heller and Zavaleta, 2009), by moving legal provisions and policies beyond listings and the eventual recovery of species and instead focus on the overall functionality of ecological systems rather than the well-being of individual species (Benson, 2012). In management terms, this also means re-assessing management strategies to better unify species-specific with system-based approaches (Benson, 2012).

Clearly, this emphasises a philosophically different viewpoint regarding the importance of biodiversity, shifting from a naturalistic view that weights species intrinsically (viewing the evolutionary record as an important resource), to a more anthropomorphic view that weights species in terms of their service or resource to humans (Rolston, 1985). However, when planning climate change adaption strategies, the implications of biodiversity loss for ecosystem functioning and stability is arguably more important, as the nonlinear dynamics of ecological systems mean the loss of species is unlikely to be linearly related to ecosystem functioning (Montoya and Raffaelli, 2010). For alpine river systems, however, limited understanding of the links between biodiversity and ecosystem function is at present a barrier to progression.

In addition, there are likely to be both ‘winners’ and ‘losers’ as climate induced habitat change alters biotic patterns (Somero, 2010). For example, shifts in aquatic subsidy dynamics (increased in-stream production) are likely to benefit insectivorous birds, mammals and reptiles (Burdon and Harding, 2008; Epanchin et al., 2010). Beyond the designation of ark sites (i.e. basins with sufficient cryospheric-flow buffering), trans-locations of taxa and possibly flow augmentation (i.e. managed coldwater discharges), the ability to protect the ‘losers’ (cold stenothermic glacial stream specialist; Brown et al., 2007) as glaciers recede and disappear is limited. As the above measures are all costly and perhaps impractical, the question becomes whether (or not) conservation should focus on (i) the ‘winners’, which may be other high altitude taxa from more stable groundwater habitats (e.g. *Habroleptoides berthelemyi, Calotriton asper* (Brown et al., 2007, 2009)), or (ii) maintaining ecosystem functioning. If the latter is preferable, it is necessary to look beyond the taxonomic composition of ecological communities and measure functions (e.g. production, decomposition, nutrient uptake). To link changes in functioning with changes in biodiversity a detailed knowledge of aquatic community traits composition, particularly at lower trophic levels, is required (Menezes et al., 2010). However, despite recent findings from North America, which illustrated that functional diversity will increase as basin glacial cover decreases (Brown and Milner 2012), our knowledge of biodiversity – ecosystem functioning relationships in alpine river systems remains limited. This research gap needs to be urgently addressed, as an understanding of how anticipated increases in alpha diversity and the loss of endemic species will influence in-stream ecological processes is vital, particularly if conservation priorities shift from the preservation of certain species to the maintenance of certain functions.

5.2. Developing Conservation Strategies for a Changing Climate in Alpine Streams

Many of the aims and objectives in the adaptation guidance provided by EU and federal level institutions are at present not well supported by actionable measures that managers can implement (Brouwer et al., 2012). Furthermore, statements on the introduction of adaptability and flexibility remain vague, without clearly stated actions prioritised or provided for site, local or regional scales. To contribute to enhancing clarity in this area, a common set of variables were identified for alpine river basins (based on the 'axes of concern' outlined in Section 2.2), which could assist the directing of conservation and adaption policies (Table 4).

A conceptual approach to conservation planning for alpine river ecosystems (adapted from Gillson et al. 2013) is summarised in Figure 6. Conservation capacity (y-axis) is particularly sensitive to flow regulation/abstraction which can reduce connectivity between and within basins, outside the natural contraction and expansion cycles associated with annual melt dynamics (Malard et al., 2006). Degradation of the intervening matrix by agricultural practices or hard infrastructure (e.g. Dickson et al., 2012) can also reduce conservation capacity (Table 5). The network sensitivity (x-axis) for alpine river ecosystems is more complicated. Although altitudinal range is wide, and therefore range expansions of more lowland taxa is possible, extinction of range restricted taxa (e.g. *Diamesa* spp. glacier stream specialists) is probable (Jacobsen et al., 2012; Finn et al., 2013). Climate sensitivity is high for alpine basins when compared to lower altitude systems due to the strong links between climate-cryosphere-hydrology-ecology (Hannah et al., 2007). However, if glacier storage (ice volume) is sufficient to maintain the characteristic hydrological regime (i.e. shift from scenario A to B: Fig. 3) network sensitivity could be considered low (e.g. as the 2050 predictions for the Rhone suggest; Fig. 5). The two test basins were placed in 'conservation axes space' based on the variables in Table 5. Due to the lower altitudinal range and cryosphere-flow buffering, and increased potential for predator invasion, the network sensitivity of the Taillon basin was considerably higher than the upper Rhone (Fig. 6).The conservation capacity of the Taillon basin was also higher than the Rhone due to the larger proportion of the basin area within a national park and lack of river flow regulation.

Non-climatic stressors to alpine river ecosystems can act as an additional filter in the climate-hydrology-biota cascade, and may interact with biological traits of organisms and alter community composition (Tockner et al., 2010). Invasive species (e.g. brook trout) and agricultural/grazing related nutrient release are of particular concern in alpine environments. For example, invasive predators are likely to have implications for both instream and terrestrial species and communities, altering body size distribution (Khamis unpublished data) and aquatic resource subsidies (Epanchin et al., 2010). In light of increased nutrient release as glaciers recede (Hood and Scott, 2008; Fountain et al., 2012), it is unclear whether community processing rates will track nutrient availability (Wilhelm et al., 2013). The loss of these important nutrient sinks (alpine rivers), may also have implications downstream (Peterson et al., 2001; Robinson et al., 2008). Therefore, we suggest developing catchment scale, area specific conservation approaches, better suited to managing additional non-climate related stressors such as intensive agriculture/livestock grazing (i.e. additional nutrient release) or the spread of invasive species.

For area based approaches to be successful, stakeholder participation is essential (Linke et al., 2011). The use of species specific action plans for flagship species within a broader area based framework has succeeded in bringing stakeholders on board in terrestrial settings (Nawaz et al. 2008). There are a number of taxa which have potential to act as alpine river flagship species, for example the Pyrenean Desman (*Galemys pyrenaicus*), which is currently listed as vulnerable by the IUCN (Fernandes et al., 2008), or the Pyrenean Newt (*Calotriton asper*) which is listed as near threatened (Bosch et al., 2009). Both of these species are likely to be winners as climate change and glacier retreat create more suitable habitats (see Fig. 5), but will be susceptible to other anthropogenic stressors. In the Swiss case, the federal flood policy has prioritised enhancing ecological resilience (Table 2) but considerable challenges remain in stakeholder buy-in during its implementation, strongly related to barriers of purchasing land from farmers or compensation payments for flooded farmland (Hill and Engle, 2013). Managing diverse stakeholder interests and rivalries (e.g. residual flows for environment versus take-offs for hydropower; flood resilience versus agriculture) is a core issue that conservation must navigate, perhaps by engaging in climate related education prior to launching specific projects, building trust between sectors and governance scales, and presenting clear economic and environmental benefits to the different stakeholders.

While policy makers are recognising increasingly the need to maximise synergies and reduce trade-offs across different policy frameworks, economic sectors and types of water infrastructure, there remains limited operationalisation of these aims (Brouwer et al., 2012; EEA, 2012; FOEN, 2012a). Potential synergies with economic infrastructure were minimal for the French Pyrénées site, while the Swiss site contained significant anthropogenic influences due to the level of hydropower infrastructure, diversion points and retention (Fatichi et al., 2013). Therefore, aligning and co-ordinating competing interests between conservation, adaptation and energy priorities is vital as part of the increasingly important process (in the context of climate change) of identifying opportunities to reduce conflict and increase synergies between conservation and local social and economic needs (Heller and Zavaleta, 2009). Well managed dams and reservoirs are an important part of integrated water management schemes under climate change conditions, in their potential contribution to water storage, flood protection and flow augmentation/releases during droughts (EC, 2009a).Conservation managers not only need to deal with the infrastructural legacies in place, but should also be enabled to work more closely with the managers of such infrastructure to develop strategies which mutually benefit human and environmental needs.

One interesting example of managing these synergies comes from a sub-alpine area in the east of Switzerland, namely the Spöl River in the Swiss National Park. In collaboration with Engadin hydroelectric power stations, artificial sporadic floods have been used to re-create a pre-dam level of natural disturbance, thereby restoring pre-dam assemblages in the macroinvertebrate community more typical of a mountain stream (Robinson, 2012).

Unfortunately, in March 2013, significant ecological damage was caused when a large quantity of sludge was accidently released into the stream. This release was in response to low river levels, but, due to exceptionally low reservoir levels, a build-up of sediment above the dam was also released (Aqueduct, 2013). The project and the incident reveal the opportunities and risks of the linkages between hydropower and conservation. Projects such as SHARE (http://www.share-alpinerivers.eu/) and collaboration at Spöl are important in the development of requisite tools to balance the competing needs of and for river ecosystems and hydropower requirements. However, this disaster provides some important lessons for how to better mitigate the potential risks associated with increasingly variable hydrological conditions. In particular low flows events and the need for regular monitoring and consideration of antecedent conditions before employing mitigation (e.g. compensation flows).

Monitoring and observation networks are critical to developing the systems understanding needed to underpin conservation strategies (Grabherr et al., 2000). For alpine flora, a global monitoring network has been established as part of the GLORIA project (GLobal Observation Research Initiative in Alpine environments). A similar, dense monitoring network exist for glaciers and has been utilised for identifying climate signals (Haeberli et al., 2007). However, while alpine river networks have been proposed as ideal indicators of hydroecological responses to climate change (Milner et al., 2009), an integrated network of monitoring sites with common protocols has yet to be established. In autumn 2013, this will be addressed by a European Science Foundation initiative entitled GLACier-fed rivers and climate change; current knowledge and future NETwork of monitoring sites (GLAC-HYDROECO-NET). Recent work has highlighted the need for a robust approach to identify and group similar glacier river types, thus enabling climate related ecosystem responses to be separated from patterns associated with habitat heterogeneity (Weekes et al., 2012).

6. Conclusion

Given the current state of international and regional climate policy, preventing predicted changes to the hydrology, physicochemical habitat and ecology of alpine rivers sourced by retreating glaciers, seems unlikely. Hence, in this context conservation strategies for alpine river systems must shift from the traditional preservation and restoration paradigms to embrace approaches based on flexibility, non-linearity, and redundancy. While traditional approaches provide fundamental protection and prevention against point and non-point source pollution, additional strategies that enable a more holistic and flexible approach to conservation in the potentially greater and more irreversible impacts of climate change.

The comparative case studies presented in this paper (i.e. Pyrénées – European Alps) highlights 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). The vulnerability of alpine environments to climate change combined with the limited ability to mitigate these changes at the local scale restricts conservation interventions to addressing local non-climate related stressors, which may reduce synergistic feedbacks and maintain future ecosystem integrity. However, unlike lowland river systems, where it is possible to intervene and reduce the impacts of climate change (e.g. planting riparian woodlands for mitigating the impacts of warming on salmonid populations (Hannah et al., 2008)), appropriate intervention strategies are more limited and complex in alpine environments.

As there is little that can be done to prevent loss of glacial river habitat, conservation measures for the protection of range restricted meltwater specialist taxa and associated unique genetic material are limited. As outlined earlier, one possibility is the implementation of managed coldwater releases which could potentially emulate the diurnal and seasonal melt cycles of glacier fed rivers. However, as this is likely to be expensive and somewhat impractical, and in some areas reservoir water may actually be warmer than the meltwater-fed rivers into which it is discharged (Dickson et al., 2012). The identification of suitable arc sites (i.e. river basins with suitable cryospheric buffering) and stocking from multiple sites to increase genetic diversity seems the most viable measure. Therefore, as habitat conditions and biotic communities will be in a state of flux, we suggest a shift is required to move provisions and policy guidance on conservation approaches from focusing on taxonomic units to functional units. Furthermore, 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) better balance the current legislative focus 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.

While there has been concern that the law itself does not easily accommodate a resilience-based perspective, more recent developments on un-packing how different facets of the legal system might foster social-ecological resilience deserve greater attention in conservation adaptation literature (Ebbesson, 2010; Garmestani and Benson, 2013; Hill et al., in review; Ruhl, 2012). Within the specific context of the legal frameworks addressed in this paper, progress towards implementing these shifts could be made by: expanding provisions and policies beyond listing of priority species (e.g. also promote long-term species diversity and ecosystem multi-functionality) to account for system functioning (e.g. define and monitor ecological shifts as a result of climate change); developing a more proactively adaptive approach by incorporating new observations and learning into conservation design through iterative review periods; better utilising regional adaptation planning processes to account for and synergies and trade-offs across mitigation and adaptation, as well as reducing tensions between conservation and different sectoral requirements on affected ecosystems (Benson, 2012).

The axes of concern framework may be used as both a tool for identifying suitable ark sites and also to question whether the current general approach to alpine ecosystems (e.g. Natura 2000) is appropriate for these diverse mountain environments. Using such a framework could help direct more targeted conservation policy to address the different stressors identified for the Swiss Alps (tourism and hydropower) and the Pyrénées (grazing and invasive species).

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Table 1. Review of conservation principles for climate change adaptation.

Priority	Description
Baseline Measures	Minimise existing, non-climate related anthropogenic stressors, to enhance general ecosystem resilience (Clarke, 2009; Hulme, 2005; Muir et al., 2012). Such measures (e.g. reducing point and diffuse pollutants) are seen as low regret, potentially reducing the risk of synergistic feedbacks with climate change and deliver large gains for biodiversity (Matthews and Le Quesne, 2009).
Flexibility/ Variability	Hydrological variability (as opposed to managing water quality or establishing minimum flows) proposed as a central tenet for sustaining ecological integrity under climate change (Monk and Wood, 2008, Poff et al., 1997 and Richter et al., 1997). Increased flexibility (e.g. buffer zones) required in the management of vulnerable ecosystems (Heller and Zavaleta, 2009) and '*inherent adaptability of species and ecosystem processes'* within them (Hulme, 2005).
Scale	Management targets need to take into account short and long term impacts of climate change and scales beyond the 'project' or 'site' at which they currently tend to reside (Matthews et al., 2011). Freshwater habitats require a more integrated approach to conservation than exclusive protected areas (Rivers-Moore et al., 2011). Clarke (2009) suggests that there are many good reasons for placing catchments or rivers at the heart of biodiversity adaptation, due to their high levels of biodiversity and intrinsic value, the potentially already existent controls on damaging activities on and off site as well as management frameworks already in place (Clarke, 2009). The temporal dynamic is equally important, and while short term strategies with more imediate results are often desireable, these must complement or be embeedded within longer term stratergies which increase resilence to climate change (Muir et al., 2012).
Connectivity	In readdressing the scale of conservation, connectivity should be re-established at the landscape scale (e.g. across protected sites; migration corridors; reinstating hydrological connectivity between river channels and floodplain wetlands) to enhance resilience during extreme events or enable migration upstream or downstream to more suitable climates (Clarke, 2009; Heller and Zavaleta, 2009; Wilby et al., 2010).
Integration	Integrating conservation requirements into other areas of adaptation or mitigation (crop choice, biofuels, flood policy) is for to minimise trade-offs across different policy frameworks that increase social, economic or ecological vulnerabilities and develop win-win measures. Ensuring land and water managers have the requisite arenas for collaborating at the relevant scales is paramount (site, catchment) (Clarke, 2009).
Priority Setting	Climate change might force managers to re-address species conservation as the central tenet of conservation, and realign their perceptions of which species can be termed 'native' or 'characteristic' of given areas (Clarke, 2009). As baseline conditions change, new assemblages are formed that managers might need to view as a new 'acceptable' ecosystem state (even with the loss of prior species), rather than incurring high costs for translocations or redesigning protected areas (Muir et al, 2012).

Table 2. Overview of the key policy and legislative frameworks that shape conservation responses in the two case areas.

Legislation	Articles	Detail	Characterisation
EU Water Framework Directive (WFD) (EC, 2000)	Preamble 11	Preservation, protection and quality improvement through prudent and rational use of natural resources.	Prevention of harm and preservation in static environments.
	Art 4 (1)	Protect and enhance the 'good status' of aquatic ecosystems.	
	Art 4 (5-7)	Temporary deterioration in status is admissible under exceptional circumstances: socio-economic conditions (5); extreme floods and prolonged droughts (6); cost grounds (7).	Ecological change as reversible.
	Art 11 (3, 8)	Periodic review (every 6 years) of controls and measures.	Iterative: changing baseline condition. Direct/Point Source
	Art 13	River Basin Management Plans (RBMP) - 6 year revision periods: climate checks on programmes of measures to identify measures that would strengthen or weaken river basins' capacity to adapt to climate change.	Step-wise and cyclical planning.
EU Habitats Directive	Art 1	Maintain or restore the natural habitats and species at a favourable status.	Ecological change as predictable and reversible. Restoration in static reserves.
	Art 3, Annex I, II	Priority habitats identified and designated special conservation status.	
	Art 6, 8	Avoidance of the deterioration of natural habitats in special areas of conservation.	
	Art 12	Measures to establish a system of strict protection for listed species.	
	Art 10	Requirement to manage landscape features of major importance for wild fauna and flora. Integration into land-use planning and development policies to improve the ecological coherence of the Natura 2000 network.	Cross-scale, accommodation of changing baseline conditions.
	Art 17	Iterative period of review that requires a review of the implementation measures for conservation every 6 years.	
7th Policy Framework for Environment	(EC, 2009b)	Aims to be '*sufficiently adaptable and flexible to respond to the increasingly inter linked nature of environmental challenges*'.	
Guidance document (24) (EC, 2009a)	RBM in a Changing Climate	Synergies promoted between directives (e.g. wetland restoration through flood management measures) to enhance resilience (river - floodplain connectivity, soil fertility, groundwater recharge, and biodiversity) to climate change impacts. Coordination and exchange of information.	
Swiss Federal Constitution	Art 78	Protection of species, and biodiversity, and particular areas of outstanding beauty and importance.	Preservation in a static environment. Direct, point source .
Swiss Federal Water Protection Act (1991) updated 2011.	Art 1	Preserve and protect natural habitats of native fauna, flora, fishing waters and natural hydrological cycles[1].	
	Art 3, 6, 12, 14.	Prevention of harm and a general prohibition for direct or indirect noxious discharge or infiltrations into any water body[2].	

[1] Supported by the Federal Act on Fisheries (1991).

	Art 30	Introduction and maintenance of residual flows.	Protection and restoration.
	Art 38a25, Art 80	Revitalisation of waterways: rehabilitation and re-naturalisation of severely impacted waterways to protect and restore aquatic eco-systems (Art.80).	Restoration in a static environment.
Swiss Federal Flood Policy	(FOEN, 2011)	Revitalisation goals to improve flood protection and maintain ecological functioning of watercourses (e.g. buffer zones, preservation or re-creation of natural retention zones for floods).	Changing baseline conditions acknowledged. Maintain historically defined community structure and function.
Swiss Federal Action Plan on Biodiversity & Strategy on Climate Change Adaptation	(FOEN, 2012b) (FOEN, 2012a)	Preserve national priority species and key habitats, prevent and control invasive species, develop ecological infrastructure for connectivity and flood resilience. Implementation through red lists[3], priority species, invasive species, as well as national parks, protected areas, reserves and ecological networks[4].	
Canton Valais Law on Hydraulic Engineering (2007)	Art.5g, 392	Protection of aquatic ecosystems, but revitalisation measures (restoring the natural functioning of waterways[5]) mainly driven by mainly driven by federal and cantonal ordinance, policy guidance and subsidy programmes (NFA, 2008).	Protection and restoration.
Canton Valais Ordinance on Hydraulic Engineering (2007)	Art. 6	Works should restore, maintain or improve key functions of waterways, including environmental functions relating to the improvement or restoration of biotopes for aquatic and riparian flora, natural connectivity and functioning, and water and landscape quality.	
	Art. 34	Subsidies available for projects that meet specific environmental criteria.	

[2] Supported by Federal Act on the Protection of Nature and Landscapes (1966), and the Federal Act on Forests (1991) as well as Federal and Cantonal Level Ordinances (see supplementary materials).
[3]http://www.bafu.admin.ch/publikationen/publikation/01631/index.html?lang=en
[4] http://www.bafu.admin.ch/naturschutz/index.html?lang=de
[5] Renaturalisation measures are defined as: All measures that aim to improve and restore the condition and natural functioning of waterways, altered by anthropogenic interventions. The aim is to protect and restore the freshwater and riparian ecosystems' biodiversity with respect to fostering sustainable development. (http://www.vs.ch/Navig/navig.asp?MenuID=4628&Language=de).

Table 3. Description of basin characteristics for the two case study locations.

Variable	Taillon	Rhone
Glacier size (km^2)	Glacier du Taillon: 0.09 Glacier des Gabietous: 0.08	Rhonegletscher: 17.6 Muttgletscher: 0.6
Basin area (km^2)	8.8	38.9
Glacier cover (%)	1.9	52.2
Altitudinal range (m)	1800 – 3144	1760-3630
Geology	Mixed sedimentary	Mostly crystalline with local calcareous outcrops
Protected area (%)	~60	8.5

Table 4. Projected changes in air temperature and precipitation for both study basins. Values are relative to the control period (1992-2010).

Basin	**Air temperature (°C)**	**Precipitation (%)**
Taillon-Gabiétous	+1.2	-5
Rhone	+0.9	+8

Table 5. Variables specific to alpine river basin conservation planning and identification of priority habitats.

Variables	**Categories**	**Score**
Conservation capacity		
Proportion within national park	High (> 50 %) Mid (25 – 50 %) Low (< 25 %)	3 2 1
Matrix state (density of energy/agriculture/tourist infrastructure)	Minimal degradation Intermediate degradation High degradation	3 2 1
Connectivity (river regulation)	High (low regulation) Mid (mid regulation) Low (high regulation)	3 2 1
Grazing pressure (Stocking density/duration)	Low Mid High	3 2 1
Network sensitivity		
Altitudinal range	Low (<500m) Mid (500-1500m) High (>1500m)	3 2 1
Cryosphere-flow buffering (see Fig 3)	Low (C scenario) Mid (B scenario) High (A scenario)	3 2 1
Abiotic diversity (e.g. Geological variability)	Low Mid High	3 2 1
Endemism rate	High Mid Low	3 2 1
Invasive species (habitat susceptibility to invasion)	High Mid Low	3 2 1

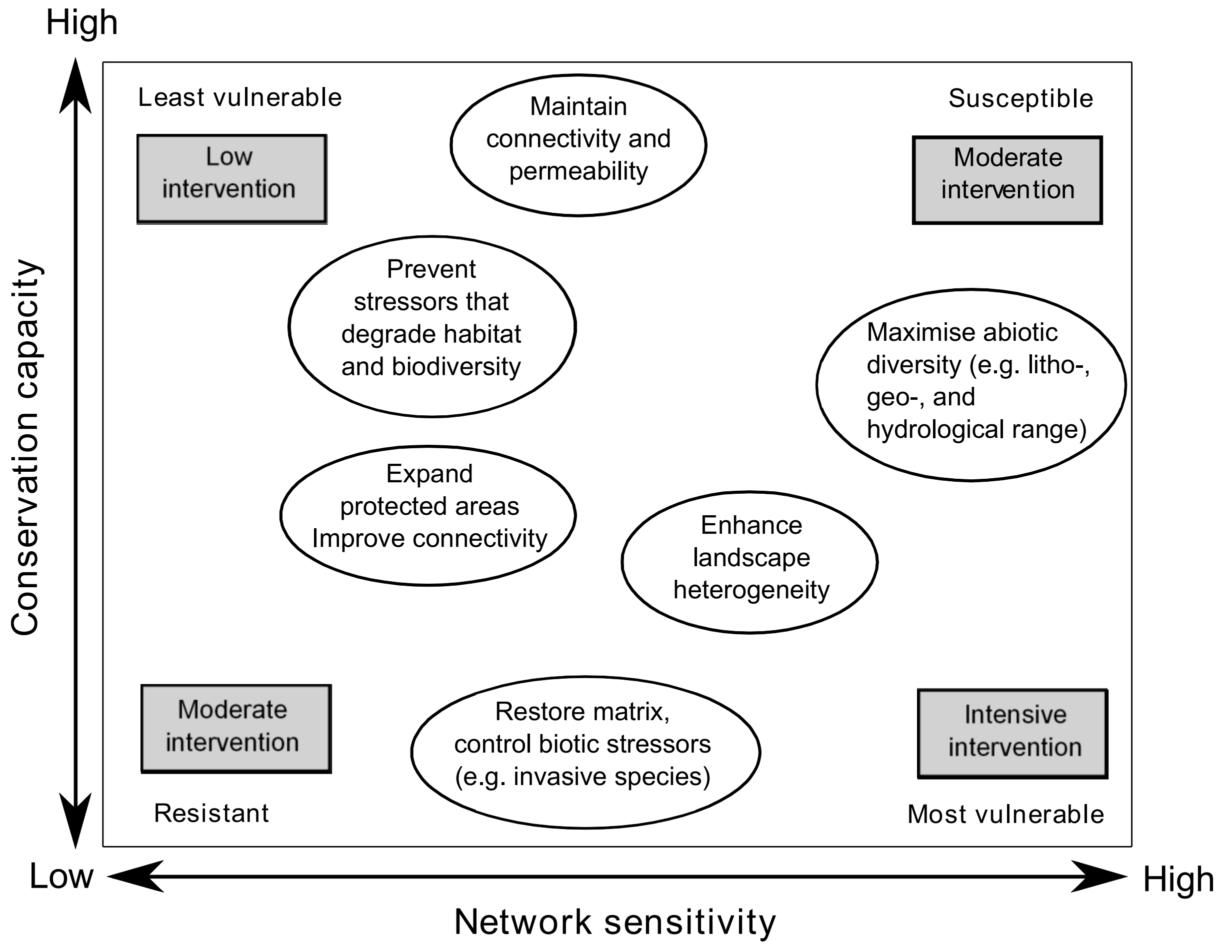

Figure 1. A conceptual approach to conservation planning based on the axes of concern (adapted from Gillson et al. (2013). Bubbles indicate proposed management intervention.

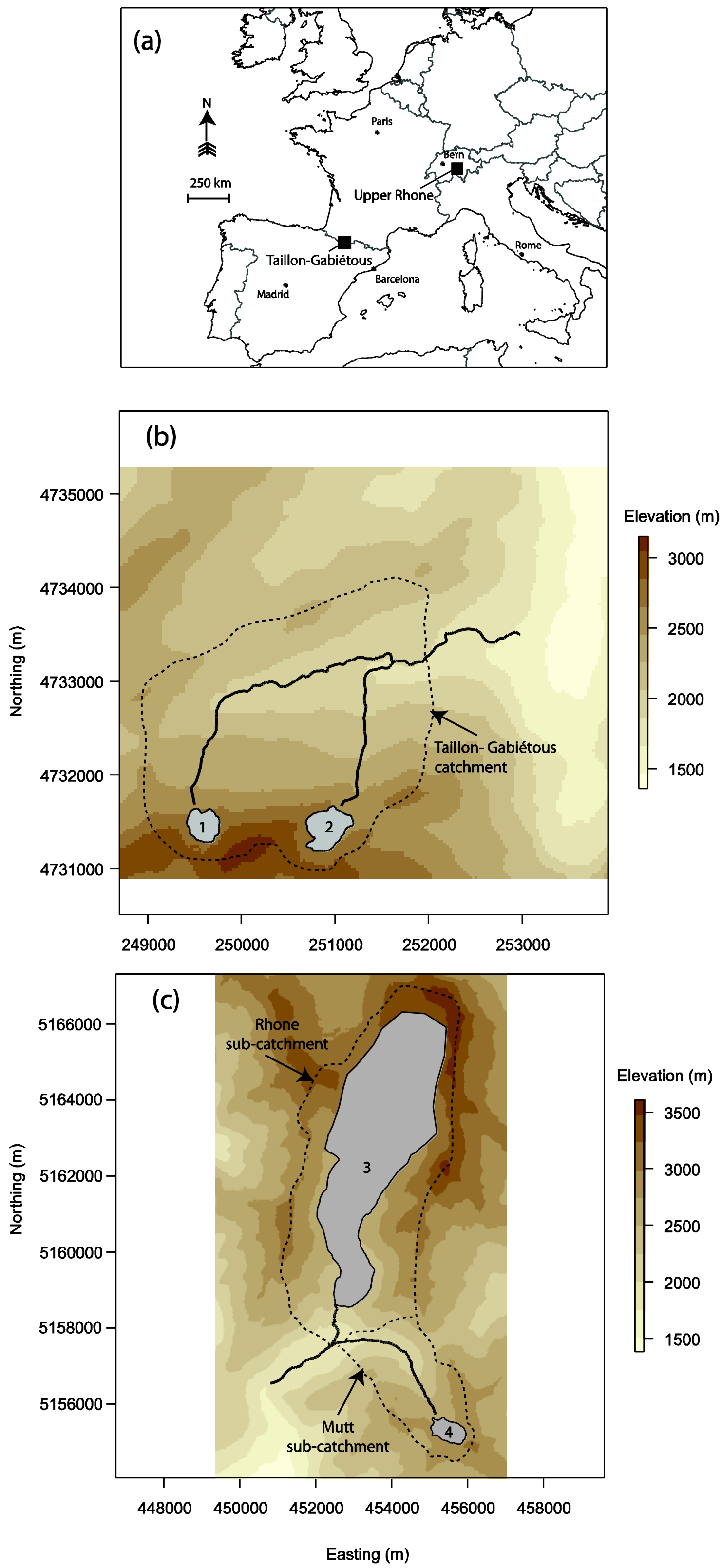

Figure 2. (a) Map of study basin locations. (b) Taillon- Gabietous catchment and (c) Upper Rhone catchment with the sub basins Mutt and Rhone delineated. For b & c dashed lines represents catchment boundaries, solid lines the main river channels. Glaciers are represented by grey shaded areas and numbered as follows: 1. Glacier des Gabiétous, 2. Glacier du Taillon, 3. Rhone glacier and 4. Mutt glacier.

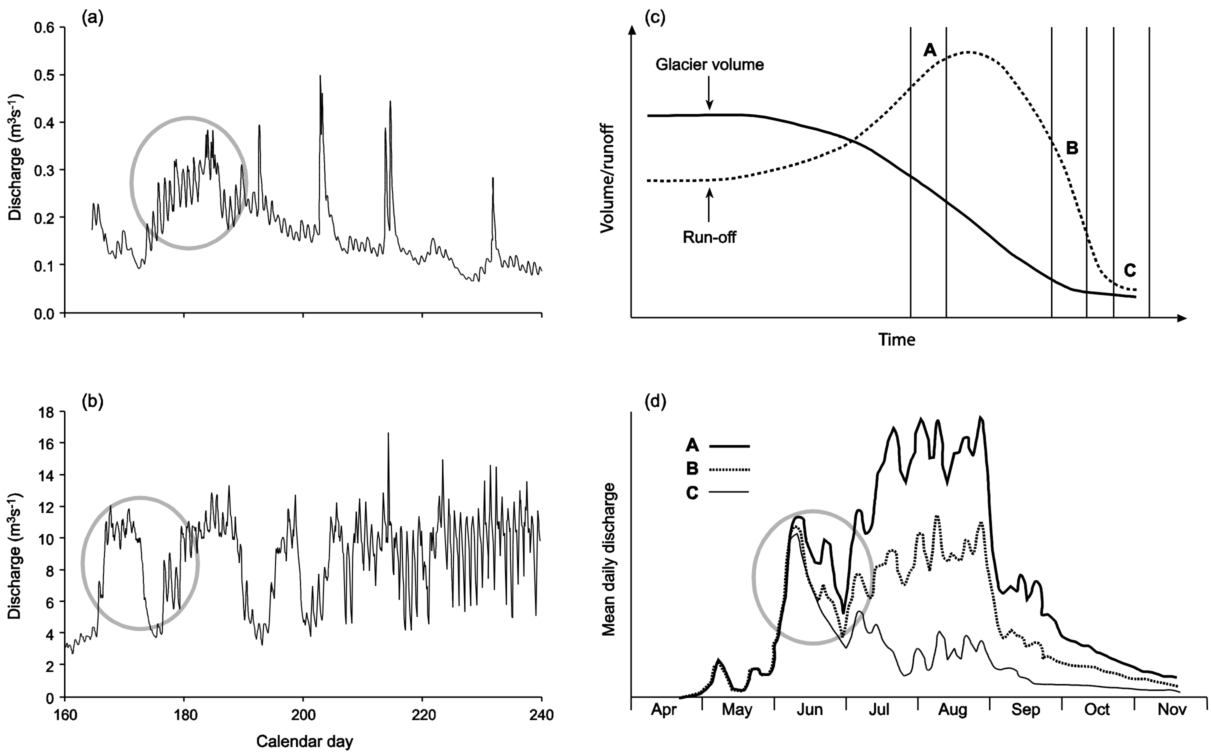

Figure 3. Discharge records from (a) the Taillon – Gabiétous catchment (2010), in the French Pyrénées and (b) the upper Rhone catchment in the Swiss Alps (2009). (c) Hypothetical relationship between runoff and glacier retreat and (d) anticipated scenarios (A, B, C) at three different stages of glacier mass reduction. Grey circles indicate June-July transition between snowmelt dominated and glacier melt dominated runoff periods.

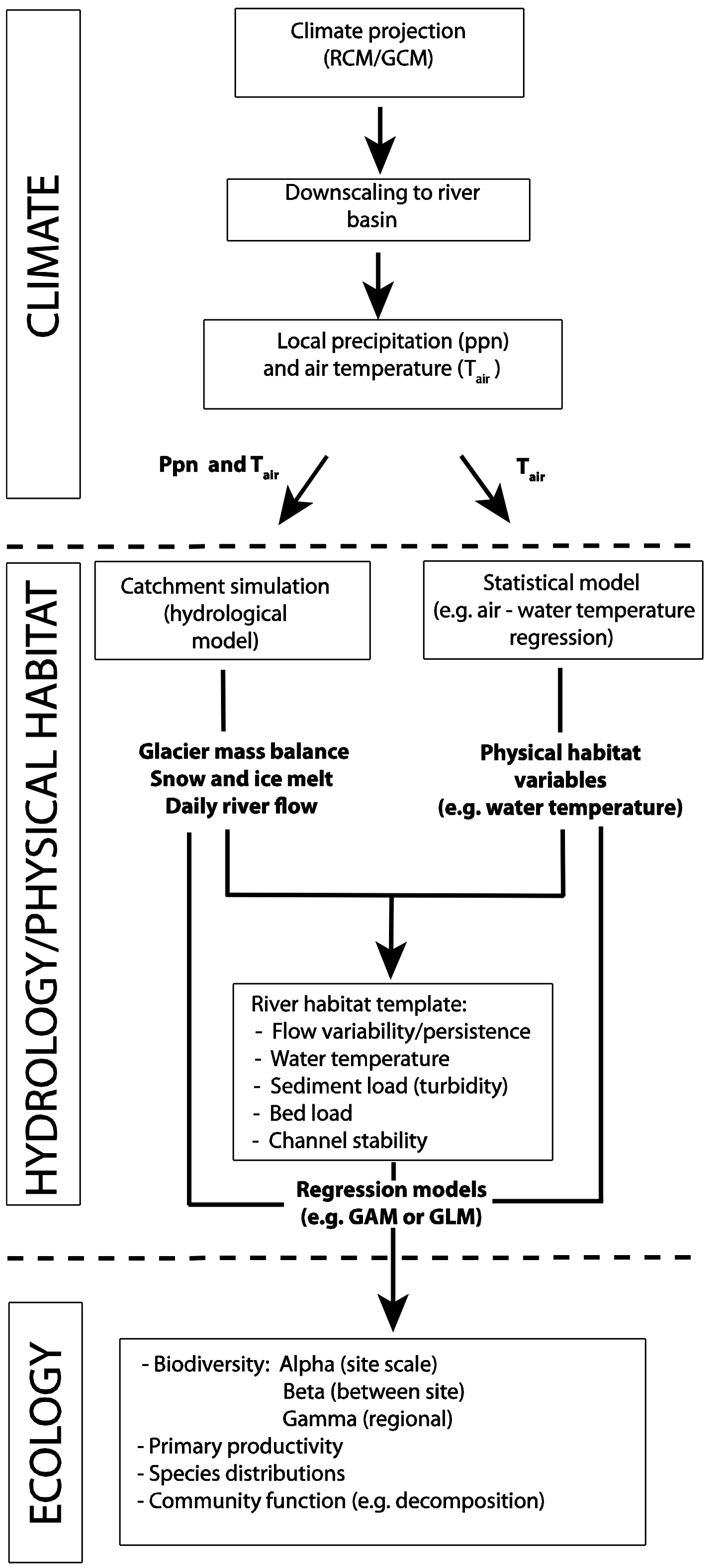

Figure 4. A conceptual approach for predicting alpine river ecosystem responses to climate change

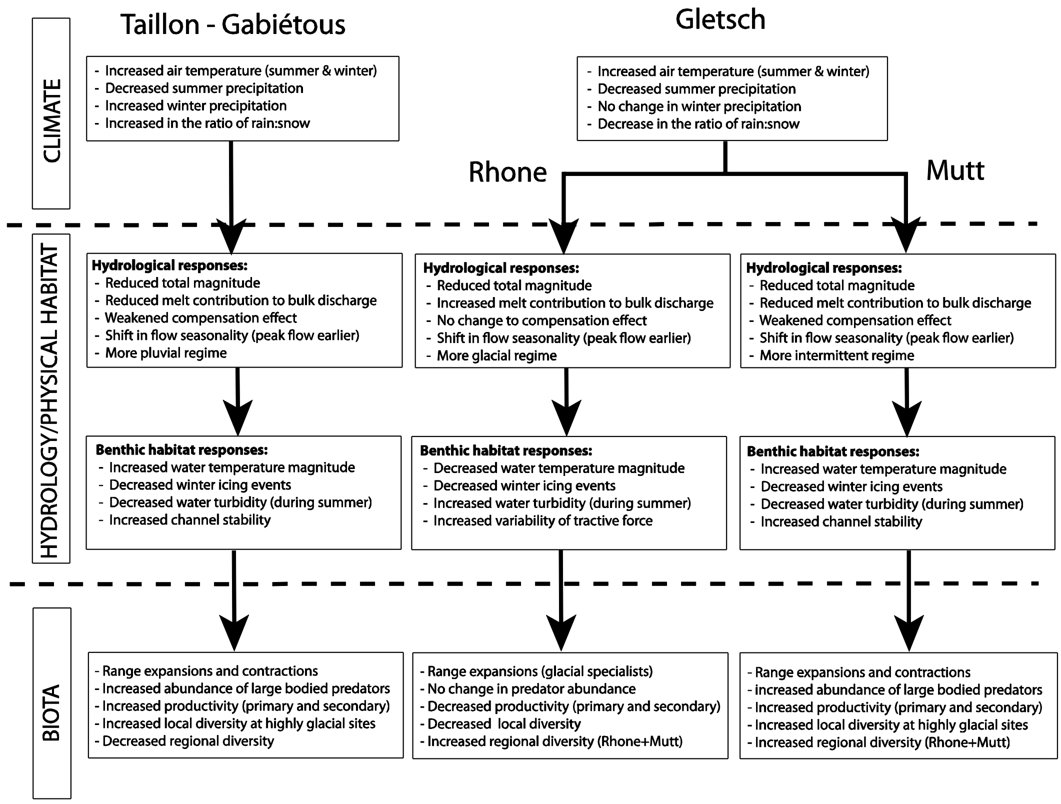

Figure 5. Predicted hydrological, physico-chemical habitat and ecological responses for the Taillon basin, French Pyrénées and two sub-catchments of the upper Rhone basin, Swiss Alps. Climate projections were based on the A1B climate scenario (REMO RCM) and hydrological predictions were obtained from a distributed rainfall-runoff model (TOPKAPI).

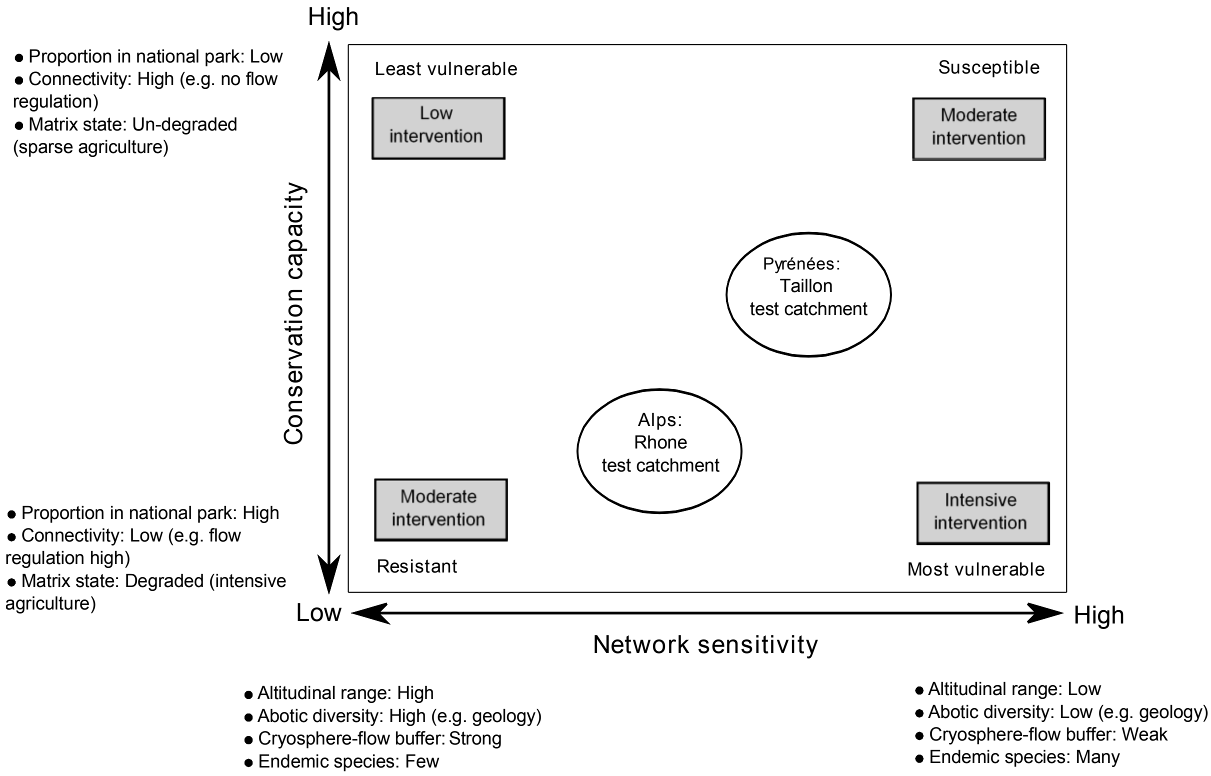

Figure 6. The axes of concern (adapted from Gillson et al. (2013)) for alpine river basin planning. The location of the two ACQWA case studies in 'conservation axes space' are displayed in bubbles.

Box 1. CARE Principles adapted from Linke et al. (2011).

Comprehensiveness:

- Conserve habitat and species baseline.
- Ensure inclusion of the full range of species, ecosystems and associated processes. Avoid bias towards specific areas or bioregions.

Adequacy:

- Effective design of conservation networks to ensure biodiversity persistence.
- Develop ecologically resilient and varied landscapes.
    - Conserve and enhance local variation within sites and habitats.
    - Make space for the natural development of rivers and coasts.
- Establish ecological networks.

Representativeness:

- Ensure the full range of biodiversity is covered with the areas chosen on the basis of comprehensiveness.
- Identify, validate and employ suitable surrogate measures for quantifying biodiversity.

Efficiency:

- Minimise conservation costs and impacts on stakeholders.