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PERSPECTIVE

The importance of indirect effects of climate change adaptations on alpine and pre-alpine freshwater systems

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Abstract

1. Freshwater is vital to much life on Earth and is an essential resource for humans. Climate change, however, dramatically changes freshwater systems and reduces water quality, poses a risk to drinking water availability and has severe impacts on aquatic ecosystems and their biodiversity.
2. The direct effects of climate change, such as increased temperatures and higher frequency of extreme meteorological events, interact with human responses to climate change, which we refer to here as 'indirect effects'. The latter possibly have even greater impact than the direct effects of climate change. Specifically, changes in land-use practices as responses to climate change, such as adjusted cropping regimes or a shift to renewable hydroelectricity to mitigate climate change, can very strongly affect freshwater ecosystems.
3. Hitherto, these indirect effects and the possibility of idiosyncratic outcomes are under-recognized. Here, we synthesize knowledge and identify threats to freshwater environments in alpine and pre-alpine regions, which are particularly affected by climate change.
4. We focus on the effects of adapted agriculture and hydropower production on freshwater quality and ecological status, as these examples have strong indirect effects that interact with direct effects of climate change (e.g., water temperature, droughts, isolation of populations).
5. We outline how failure to effectively account for indirect effects associated with human responses to climate change may exacerbate direct climate change impacts on aquatic ecosystems. If managed properly, however, human responses to indirect effects offer potential for rapid and implementable leverage to mitigate some of the direct climate change effects on aquatic ecosystems. To better address looming risks, policy- and decisionmakers must account for indirect effects and incorporate them into restoration planning and the respective sectorial policies.

KEYWORDS
agriculture, aquatic ecosystems, climate change, ecosystem change, hydropower, land-use, water quality

1 | INTRODUCTION

Freshwater biodiversity and the functioning of freshwater ecosystems are declining at unprecedented rates (Albert et al., 2021; Dudgeon, 2019; Reid et al., 2019). Nearly 80% of the world's population is exposed to high levels of threat to water security and biodiversity loss (Vorosmarty et al., 2010), 8%–16 % of freshwater species are extinct or critically endangered, and decline in freshwater populations is exceeding that of any other habitat type (Albert et al., 2021; Dudgeon, 2019; Reid et al., 2019). Climate change has well-known direct effects on aquatic systems (Heino et al., 2009; Woodward et al., 2010), such as increased water temperatures and altered river flow regimes due to changes in precipitation (Doll & Zhang, 2010; van Vliet et al., 2013), leading to range shifts and changes in the distribution of aquatic organisms (Alahuhta et al., 2011). Effects of climate change on aquatic ecosystems are expected in all biomes, but alpine and pre-alpine regions—key provider of water resources upon which 1.5 billion people depend (Viviroli et al., 2020)—are predicted to be particularly affected by climate change (Parker et al., 2008; Primicerio et al., 2007). These regions are not only undergoing higher-than-average warming (Brunetti et al., 2009), but are furthermore transformed by massive changes in the timing of discharge and runoff regimes due to the retreat and vanishing of glaciers (Beniston et al., 2018; Pellicciotti et al., 2014).

Besides direct climate change effects, it is well established that the state and quality of aquatic systems depends strongly on other anthropogenic activities, such as flow regulation, land-use or chemical pollution (Benateau et al., 2019; Dudgeon, 2019; Kaelin & Altermatt, 2016; Vorosmarty et al., 2010). Importantly, climate change and these other drivers can also interact (Figure 1). Here, we highlight how modifications in land-use or changes in economic practices, as consequences of or adaptation to climate change, may have cascading and triggering effects on aquatic systems, herein referred to as 'indirect effects'. The study of such interactive effects, empirically done for individual species such as brown trout (Borgwardt et al., 2020) or by modelling (Mantyka-Pringle et al., 2014), has only recently been undertaken at larger scales. Due to complex interactions between multiple drivers, however, it is a non-trivial task to predict the impact and extent of these combined effects (O'Connor et al., 2012) and to plan conservation strategies for freshwater ecosystems (Bush et al., 2014). For instance, the combination of severe droughts punctuated by extreme rainfall due to climate change can result in pollution peaks in water bodies (IPCC, 2021). This is particularly true in catchments that are under intense anthropogenic pressure, where pollution peaks can originate in combined sewer outflows in urban catchments, or from fertilizers and pesticides in agricultural catchments (Benateau et al., 2019). Similarly, in rivers, where water temperature depends on tree coverage as well as on air temperature, deforestation or reforestation of riparian vegetation increase or decrease the water temperatures to an even greater extent than by direct global warming (Caissie, 2006; Justice et al., 2017), with temperature fluctuations sometimes being greater than 10°C (Hester & Doyle, 2011). Thus, cutting or replanting riparian forests, resulting from climate-change motivated land-use modifications, may have stronger and faster consequences on streams than those expected from direct climate change effects. In light of such threats to rivers worldwide, Tonkin et al. (2019) have highlighted the need for better predictions of likely changes in these ecosystems. We propose that indirect effects may, at least in the short term, overrun the impact of direct climate change on water bodies, and thus must be considered in policy making, but without compromising efforts against the overarching goal of stopping or reversing climate change itself. We provide a visual summary of our argumentation in Figure 2, which is based on the extensive review by Benateau et al. (2019), partly built with individual interviews and discussions with experts (see also the Supporting Information). We qualitatively compare direct and indirect

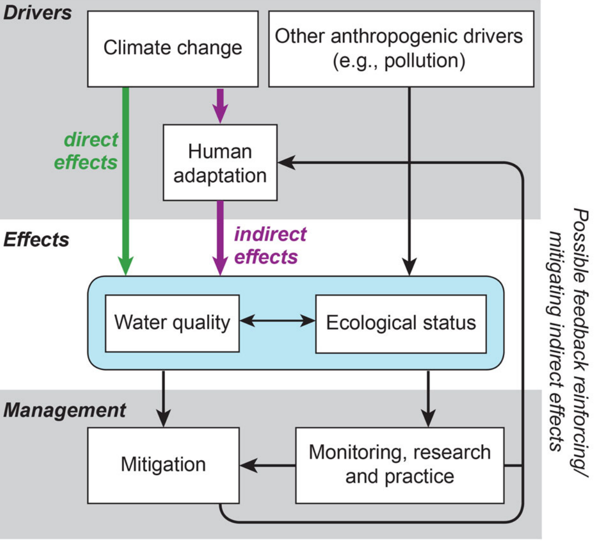

FIGURE 1 Interactions between climate change and anthropogenic drivers, their effects on freshwater ecosystems (water quality and ecological status) and their consequences on human's responses to changes with respect to management and mitigation. Climate change has well-known direct effects on water quality/quantity and ecological status of freshwater ecosystems (green arrow). The indirect effects through human adaptation (purple arrows), such as changes in in land-use practices, are less known but may be more influential and also cause feed-back loops. Black arrows indicate additional pathways mentioned in this article

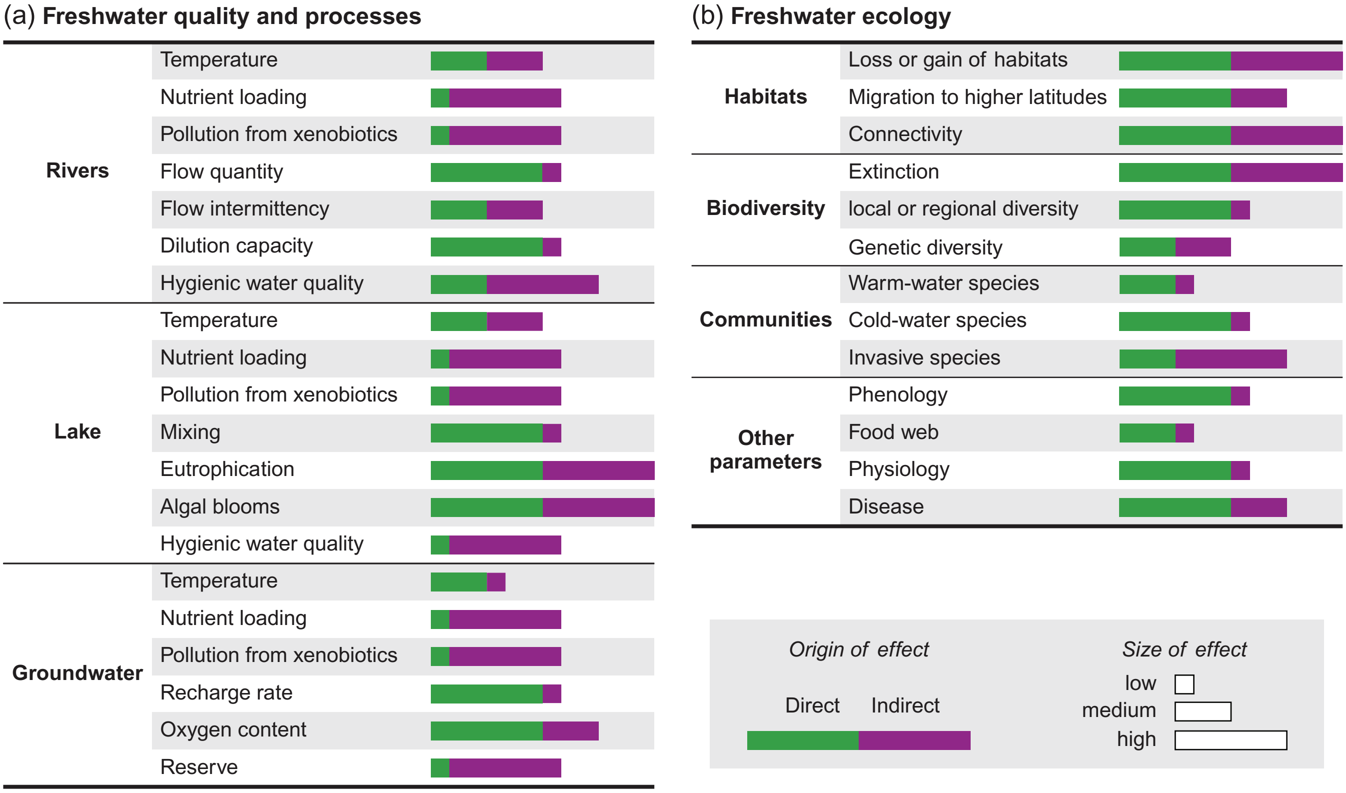

FIGURE 2 Qualitative summary of direct and indirect effect sizes of climate change on freshwater systems. (a) Effects on water quality and processes. (b) Effects on ecosystems. Figure partly based on data synthesized in Benateau et al. (2019), for further details see also supplementary information

effect size of climate change on both freshwater quality and processes as well as on freshwater ecology in order to identify areas of mitigations. Overall, direct and indirect climate change effects on aquatic systems often have similar effect sizes (Figure 2). A major consequence of anthropogenic activities is an increasing concentration of nutrients and pollutants in all aquatic habitats observed worldwide, mostly induced by agriculture. Another strong consequence is thermal and structural habitat degradation. In alpine regions, this is often associated with hydropower plants. In this perspective, we focus on indirect effects of climate change caused by hydropower and agriculture as examples of mitigation and adaption to climate change, respectively. Both have strong influences on alpine and pre-alpine regions, and deep socio-economic repercussions, but also offer fast, strong and implementable leverage to mitigate climate change effects on aquatic ecosystems.

We highlight that human responses to climate change (indirect effects) can markedly intensify most of the direct effects on water-bodies, for instance by withdrawing water for irrigation from depleting catchments during more and more frequent and extreme droughts (see Box 1). However, optimization of water utilization also has a remarkable potential to preserve freshwater habitats, biodiversity and quality. We conclude that managers and policymakers must account for indirect effects of climate change and incorporate them into restoration planning and consider these indirect effects in pertinent sectorial policies, such as agriculture or energy production.

2 | HUMAN RESPONSES (INDIRECT EFFECTS) TO CLIMATE CHANGE

2.1 | Water use for energy production

Global electricity consumption has grown nearly each year since 1974, with a shift towards renewables (IEA, 2021). Hydropower is the largest source of renewable energy, accounting for 16% of the world's generated electricity in 2019, while combined output from wind, solar and geothermal energy only reached 8.4% (IEA, 2021). In many alpine regions, surface freshwater is commonly used for hydropower production, for instance accounting for up to 64% of the domestic electricity production in the European Alps (Björnsen Gurung et al., 2016). Hydropower includes both large dams (Zarfl et al., 2019) as well as in-stream hydropower plants (Lange et al., 2018). Importantly, hydroelectric energy is often used to reduce the greenhouse gas footprint of energy production and thus is seen as a direct approach in mitigating climate change (Berga, 2016). However, it often has large detrimental effects on aquatic systems. These indirect effects include changes in hydrology and fragmentation that affect fauna and flora that are already subject to the direct effects of climate change (Datry et al., 2014). Big dams have long been known as factors of habitat destruction and ecological fragmentation (Belchik et al., 2004; Liermann et al., 2012; Wu et al., 2004). However, a growing number of studies also suggests that, by reducing downstream flow and creating obstacles, the multiplication of small hydropower plants in alpine settings also creates habitat fragmentation to an alarming extent (Lange et al., 2018). In riverine systems, biodiversity is strongly associated with the network connectivity (Altermatt, 2013). Fragmentation or inter-basin water transfers for hydroelectric installations, being known to affect whole river networks (Grill et al., 2015), thus have strong effects on ecology of aquatic organisms. For example, the isolation of populations in river leads to loss of local genetic diversity (Horreo et al., 2011). To leverage seasonal fluctuations in flow regimes, water reservoirs are built (Brunner et al., 2019). While this may be beneficial for energy production, they also affect natural run-off dynamics, sediment transport and hydrology (Evette et al., 2011), and thus can have negative effects on the specific fauna adapted to more natural hydrological regimes. Moreover, such reservoirs have been shown to be 'stepping-stones' for aquatic species invasion, establishment of which may also be directly promoted by climate change (Havel et al., 2015), and thus can have further negative consequences on the aquatic communities. Overall, adapted water usage for energy production as a human adaptation and mitigation for climate change, modifies the hydrology of freshwater systems and may exacerbate the direct negative effects of climate change on aquatic systems.

2.1.1 | Recommendations

Building or removing dams, and changes to the managed flow regimes have strong effects on the aquatic systems with respect to connectivity and hydrology including sediment budgets. Ecosystems can recover within a few years after dam removal, with organisms that have high rates of population turnover recovering even faster (Foley et al., 2017). Alternatively, future dams, especially at highest elevation, could act as water reservoirs, bridging summer droughts in areas where glaciers will be gone within a few decades. At worst, loss of glaciers and intense hydroelectric usage of remaining water would result in a complete desiccation of large sections of alpine streams. At best, moderate use and sufficient retention of meltwater could bridge otherwise future drought periods and guarantee flow continuity in alpine streams. Modifications of hydropower use can be associated with economic or social conflicts, and involvement of stakeholders is crucial to communicating and finding compromises such as fish passages (Lejon et al., 2009). Thus, the exact location and intensity of hydropower production and percentage of run-off water retained will decide if dam-building as a mitigation to climate change has positive or negative indirect effects on the functioning and biodiversity of aquatic systems.

2.2 | Agricultural and pastoralism practices

Mountains are home to 15% of the world's human population that strongly relies on agriculture and pastoralism for food and income. These activities are particularly affected by climate variability altering crop cycles, causing unpredictable yields or crop failure, and by climate-induced disasters such as floods, drought and storms (Romeo et al., 2020). Agricultural practices can have very strong effects on water quality and the ecological state of freshwater systems through two main pathways. First, the use of irrigation by agricultural systems, next to rainfall, has consequences on the hydrology and water availability of freshwaters (Gentle & Maraseni, 2012). Second, the use of agrochemicals affects water quality and the ecological communities therein (Burdon et al., 2019). Both of these pathways may be strongly affected by climate change through direct but also indirect effects. The direct effects of climate change on land-use, and the resulting human adaptations (e.g., optimization of irrigation infrastructures, flood prevention, crop modification, diversification and rotation, breeding livestock for greater tolerance, improving fertilizing applications) are well documented (Jacobs et al., 2019), but studies mostly fail to address the repercussions of these adaptations on aquatic systems. We believe that indirect effects will likely have faster, stronger and potentially more variable effects on aquatic systems, at least in the short-term, than the predicted direct long-term effects of climate change.

An increasingly dry and less predictable climate (as a direct consequence of climate change) will make rain-fed agriculture shift to irrigated agriculture by redirecting and withdrawing water from freshwater habitats, and will require increasing amounts of water during some periods of the year (Wriedt & Bouraoui, 2009). This use of water for agriculture can have severe impacts on aquatic organisms (see Belchik et al., 2004 and Box 1 for an example with high socio-economic and ecological relevance). Under the impact of climate change, agricultural activities can cause increased pressure on water quantity (due to irrigation needs) but also on water quality due to increased nitrate leaching during intensifying winter precipitations for example (Zarrineh et al., 2020). The use of agrochemicals is dependent on the agricultural type (e.g., growing crops is associated with higher pesticide use than dairy farming), and changes in agricultural practices due to climate change can have large effects on freshwaters. In alpine and pre-alpine areas, rain-fed dairy farming is currently the most predominant form of agriculture, but in the future these grasslands may become more and more dependent on irrigation. In an effort to alleviate irrigation demand, cattle may be replaced by other ruminants, or grasslands may even be replaced by different cropping systems, more adapted to rising temperatures and increasing lengths of growing seasons, but with different pest sensitivities and greater use of agrochemicals. For instance, the extent of vineyards is strongly correlated with climatic conditions (Mozell & Thach, 2014), as are the vineyard-associated side effects of pesticides on aquatic systems (Sabatier et al., 2014). An expansion of vineyards due to climate change making novel regions favourable for this type of agricultures would thus possibly have cascading effects on water quality and the ecological status of freshwater habitats in these areas.

In general, expansion of crops to new areas modifies land-use and can spread water conflict and water quality issues. Yet climate change may also result in shifts to completely novel cropping systems or crop types with lower impact on waterbodies. For example, in Central

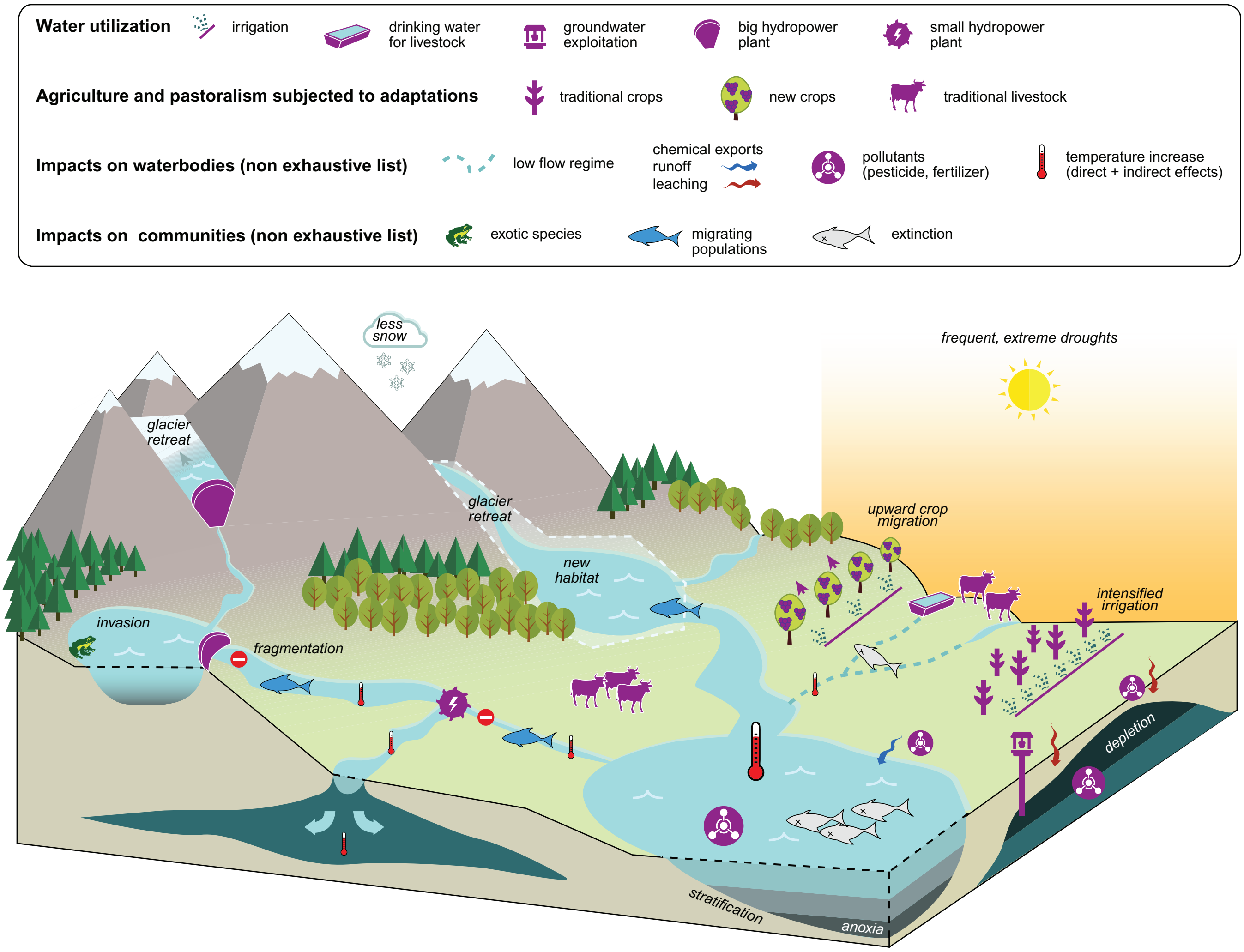

FIGURE 3 Graphic synthesis of the combination of direct and indirect effects of climate change on aquatic environments in alpine and pre-alpine settings. We focus here on hydropower and agriculture. For a detailed explanation of the causes and consequences of the individual effects, see supplement and Benateau et al. (2019)

Europe, shifts from growing potatoes (*Solanum tuberosum*, Solanaceae) to growing sweet potatoes (*Ipomoea batatas*, Convolvulaceae) have been recently seen in areas where the latter could not have been grown for climatic reasons even a few decades ago. The cultivation of sweet potatoes, which are more resilient to drought and requiring fewer pesticides, is a shift in production that can have a major influence on water use and water quality.

2.2.1 | Recommendations

New agricultural incentives should be taken after basin-wide assessments of both direct and indirect effects of climate change. Indeed, it is crucial to evaluate the indirect effects of new practices on aquatic systems to ensure that they are neutral or beneficial to mitigate direct climate change effects. Transition to novel crops should not only be evaluated with respect to the crop's climate niche and cultivability, but also with respect to water requirements and fertilizer or pesticide footprints on aquatic systems. The same is true for water-saving methods. For instance, rainwater harvesting, a practice recommended to alleviate water scarcity, could reduce streamflow and thus impede groundwater reservoir recharge, which is threatened by depletion worldwide mostly as a result of agriculture (Konikow & Kendy, 2005). Importantly, in many countries, agricultural practices are strongly directed through regulations and incentives (mostly financial subsidies). These act as strong and fast leverages with proven effectiveness to reduce negative impacts of climate change on freshwaters (Lehmann & Finger, 2014; Zhu et al., 2018). In alpine regions with many dams, hydropower reservoirs can mitigate the decrease of run-off due to drought or disappearing glaciers, and thus contribute to irrigation and river connectivity. Stored water can be retained and released more evenly across the seasons, guaranteeing flow continuity in streams as well as hydropower production. This must critically include a careful division of available water.

BOX 1. THE KLAMATH RIVER SALMONID KILL

The Klamath River flows through the Klamath Mountains (California, USA) and is home to many cold-water fish species, most notably salmon. In 2000, it faced the largest salmon kill in the history of the United States. The kill was due to the combination of direct and indirect effects of climate change. Critical drivers were (1) intense drought and (2) unusual low flowrate due to upstream utilization of water for distributed irrigation in agriculture. Extreme temperatures perturbed the fishes' migration and induced high fish density in warm water, providing ideal conditions for the proliferation of parasites and pathogens. These direct effects were aggravated by indirect effects: water diverted for the benefit of farmers aiming to mitigate the consequences of the drought on agriculture, resulted in even lower flow rates, causing the death of 34,000–70,000 salmonid fishes. This event had severe aftermaths on the fishing-dependent local economy, but also on traditional, cultural and spiritual practices (May, 2018). Belchik et al. (2004) concluded that if the flow from Iron Gate Dam had been higher (as in previous years), and less water used for irrigation, the fish kill would likely not have occurred. This illustrates the importance of supervision and optimization of human adaptations to climate change.

3 | CONCLUDING REMARKS

Climate change is transforming and will further transform many aspects of aquatic environments and ecosystems to dramatic extents (Reid et al., 2019), particularly in alpine and pre-alpine regions. We strongly support all measures to stop climate change and to reduce its direct effects. However, it is unrealistic to expect that all direct climate change effects can be reversed in the short-term, or for freshwater systems to return to pre-industrial thermal and chemical conditions. Yet, indirect effects of climate change can exceed the direct effects, and potentially have faster, stronger and more severe (negative) effects on the water quality and ecological state of alpine freshwater systems (see Figures 2 and 3). However, if managed properly, they also offer tremendous potential for rapid and implementable leverage to mitigate climate change effects on aquatic ecosystems. In fact, sensible water policies can both reduce water exploitation and preserve existing water resources. To better address looming risks, policy- and decisionmakers must consider freshwaters as a pivotal resource for humans and as highly valuable ecosystems, in order to account for indirect climate change effects, and incorporate possible indirect effects into restoration planning and relevant sectorial policies.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS' CONTRIBUTIONS

C.S. and F.A. developed the project idea. S.B., A.G., C.S. and F.A. wrote an initial report. M.B. and F.A. wrote the first draft of the manuscript, with comments from all coauthors.

DATA AVAILABILITY STATEMENT

This is a perspective article so there are no data associated with this manuscript.

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REFERENCES

Alahuhta, J., Heino, J., & Luoto, M. (2011). Climate change and the future distributions of aquatic macrophytes across boreal catchments. *Journal of Biogeography*, *38*(2), 383–393. https://doi.org/10.1111/j.1365-2699.2010.02412.x

Albert, J. S., Destouni, G., Duke-Sylvester, S. M., Magurran, A. E., Oberdorff, T., Reis, R. E., Winemiller, K. O., & Ripple, W. J. (2021). Scientists' warning to humanity on the freshwater biodiversity crisis. *AMBIO*, *50*(1), 85–94. https://doi.org/10.1007/s13280-020-01318-8

Altermatt, F. (2013). Diversity in riverine metacommunities: A network perspective. *Aquatic Ecology*, *47*, 365–377.

Belchik, M., Hillemeier, D., & Pierce, R. M. (2004). The Klamath River fish kill of 2002; analysis of contributing factors. *Yurok Tribal Fisheries Program*, *2*(3), 42.

Benateau, S., Gaudard, A., Stamm, C., & Altermatt, F. (2019). Climate change and freshwater ecosystems: Impacts on water quality and ecological status. Hydro-CH2018 Project, BAFU. Federal Office for the Environment (FOEN).

Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L. M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., & Huss, M. (2018). The European mountain cryosphere: A review of its current state, trends, and future challenges. *The Cryosphere*, *12*(2), 759–794. https://doi.org/10.5194/tc-12-759-2018

Berga, L. (2016). The role of hydropower in climate change mitigation and adaptation: A review. *Engineering*, *2*(3), 313–318. https://doi.org/10.1016/J.ENG.2016.03.004

Björnsen Gurung, A., Borsdorf, A., Füreder, L., Kienast, F., Matt, P., Scheidegger, C., Schmocker, L., Zappa, M., & Volkart, K. (2016). Rethinking pumped storage hydropower in the European Alps. *Mountain Research and Development*, *36*(2), 222–232. https://doi.org/10.1659/MRD-JOURNAL-D-15-00069.1

Borgwardt, F., Unfer, G., Auer, S., Waldner, K., El-Matbouli, M., & Bechter, T. (2020). Direct and indirect climate change impacts on brown trout in central Europe: How thermal regimes reinforce physiological stress and support the emergence of diseases. *Frontiers in Environmental Science*, *8*, 59. https://doi.org/10.3389/fenvs.2020.00059

Brunetti, M., Lentini, G., Maugeri, M., Nanni, T., Auer, I., Bohm, R., & Schoner, W. (2009). Climate variability and change in the Greater Alpine Region over the last two centuries based on multi-variable analysis. *International Journal of Climatology*, *29*(15), 2197–2225. https://doi.org/10.1002/joc.1857

Brunner, M. I., Gurung, A. B., Zappa, M., Zekollari, H., Farinotti, D., & Stähli, M. (2019). Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. *Science of the Total Environment*, *666*, 1033–1047. https://doi.org/10.1016/j.scitotenv.2019.02.169

Burdon, F. J., Munz, N. A., Reyes, M., Focks, A., Joss, A., Räsänen, K., Altermatt, F., Eggen, R. I. L., & Stamm, C. (2019). Agriculture versus wastewater pollution as drivers of macroinvertebrate community structure in streams. *Science of the Total Environment*, *659*, 1256–1265. https://doi.org/10.1016/j.scitotenv.2018.12.372

Bush, A., Hermoso, V., Linke, S., Nipperess, D., Turak, E., & Hughes, L. (2014). Freshwater conservation planning under climate change: Demonstrating proactive approaches for Australian Odonata. *Journal of Applied Ecology*, *51*(5), 1273–1281. https://doi.org/10.1111/1365-2664.12295

Caissie, D. (2006). The thermal regime of rivers: A review. *Freshwater Biology*, *51*(8), 1389–1406. https://doi.org/10.1111/j.1365-2427.2006.01597.x

Datry, T., Larned, S. T., & Tockner, K. (2014). Intermittent rivers: A challenge for freshwater ecology. *BioScience*, *64*(3), 229–235. https://doi.org/10.1093/biosci/bit027

Doll, P., & Zhang, J. (2010). Impact of climate change on freshwater ecosystems: A global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences*, *14*(5), 783–799. https://doi.org/10.5194/hess-14-783-2010

Dudgeon, D. (2019). Multiple threats imperil freshwater biodiversity in the Anthropocene. *Current Biology*, *29*(19), R960-R967. https://doi.org/10.1016/j.cub.2019.08.002

Evette, A., Peyras, L., François, H., & Gaucherand, S. (2011). Environmental risks and impacts of mountain reservoirs for artificial snow production in a context of climate change. *Journal of Alpine Research| Revue de géographie alpine*, *99*, 4. https://doi.org/10.4000/rga.1481

Foley, M. M., Bellmore, J., O'Connor, J. E., Duda, J. J., East, A. E., Grant, G., Anderson, C. W., Bountry, J. A., Collins, M. J., & Connolly, P. J. (2017). Dam removal: Listening in. *Water Resources Research*, *53*(7), 5229–5246. https://doi.org/10.1002/2017WR020457

Gentle, P., & Maraseni, T. N. (2012). Climate change, poverty and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environmental Science & Policy*, *21*, 24–34. https://doi.org/10.1016/j.envsci.2012.03.007

Grill, G., Lehner, B., Lumsdon, A. E., MacDonald, G. K., Zarfl, C., & Liermann, C. R. (2015). An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, *10*(1), 015001.

Havel, J. E., Kovalenko, K. E., Thomaz, S. M., Amalfitano, S., & Kats, L. B. (2015). Aquatic invasive species: Challenges for the future. *Hydrobiologia*, *750*(1), 147–170. https://doi.org/10.1007/s10750-014-2166-0

Heino, J., Virkkala, R., & Toivonen, H. (2009). Climate change and freshwater biodiversity: Detected patterns, future trends and adaptations in northern regions. *Biological Reviews*, *84*(1), 39–54. https://doi.org/10.1111/j.1469-185X.2008.00060.x

Hester, E. T., & Doyle, M. W. (2011). Human impacts to river temperature and their effects on biological processes: A quantitative synthesis 1. *Journal of the American Water Resources Association*, *47*(3), 571–587. https://doi.org/10.1111/j.1752-1688.2011.00525.x

Horreo, J. L., Martinez, J. L., Ayllon, F., Pola, I. G., Monteoliva, J. A., Héland, M., & Garcia-Vazquez, E. (2011). Impact of habitat fragmentation on the genetics of populations in dendritic landscapes. *Freshwater Biology*, *56*(12), 2567–2579. https://doi.org/10.1111/j.1365-2427.2011.02682.x

IEA. (2021). *Electricity production*. IEA. https://www.iea.org/reports/electricity-information-overview/electricity-production

IPCC. (2021). Summary for policymakers (Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Issue. C. U. Press.

Jacobs, C., Berglund, M., Kurnik, B., Dworak, T., Marras, S., Mereu, V., & Michetti, M. (2019). Climate change adaptation in the agriculture sector in Europe (9294800725). EEA Report No 4. EEA.

Justice, C., White, S. M., McCullough, D. A., Graves, D. S., & Blanchard, M. R. (2017). Can stream and riparian restoration offset climate change impacts to salmon populations? *Journal of Environmental Management*, *188*, 212–227. https://doi.org/10.1016/j.jenvman.2016.12.005

Kaelin, K., & Altermatt, F. (2016). Landscape-level predictions of diversity in river networks reveal opposing patterns for different groups of macroinvertebrates. *Aquatic Ecology*, *50*, 283–295.

Konikow, L. F., & Kendy, E. (2005). Groundwater depletion: A global problem. *Hydrogeology Journal*, *13*(1), 317–320. https://doi.org/10.1007/s10040-004-0411-8

Lange, K., Meier, P., Trautwein, C., Schmid, M., Robinson, C. T., Weber, C., & Brodersen, J. (2018). Basin-scale effects of small hydropower on biodiversity dynamics. *Frontiers in Ecology and the Environment*, *16*(7), 397–404. https://doi.org/10.1002/fee.1823

Lehmann, N., & Finger, R. (2014). Economic and environmental assessment of irrigation water policies: A bioeconomic simulation study. *Environmental Modelling & Software*, *51*, 112–122. https://doi.org/10.1016/j.envsoft.2013.09.011

Lejon, A. G., Renöfält, B. M., & Nilsson, C. (2009). Conflicts associated with dam removal in Sweden. *Ecology and Society*, *14*(2), 4. https://www.jstor.org/stable/26268322

Liermann, C. R., Nilsson, C., Robertson, J., & Ng, R. Y. (2012). Implications of dam obstruction for global freshwater fish diversity. *BioScience*, *62*(6), 539–548. https://doi.org/10.1525/bio.2012.62.6.5

Mantyka-Pringle, C. S., Martin, T. G., Moffatt, D. B., Linke, S., & Rhodes, J. R. (2014). Understanding and predicting the combined effects of climate change and land-use change on freshwater macroinvertebrates and fish. *Journal of Applied Ecology*, *51*(3), 572–581. https://doi.org/10.1111/1365-2664.12236

May, T. (2018). *Salmon is everything: Community-based theatre in the Klamath watershed*. Oregon State University Press.

Mozell, M. R., & Thach, L. (2014). The impact of climate change on the global wine industry: Challenges & solutions. *Wine Economics and Policy*, *3*(2), 81–89. https://doi.org/10.1016/j.wep.2014.08.001

O'Connor, M. I., Selig, E. R., Pinsky, M. L., & Altermatt, F. (2012). Toward a conceptual synthesis for climate change responses. *Global Ecology and Biogeography*, *21*(7), 693–703. https://doi.org/10.1111/j.1466-8238.2011.00713.x

Parker, B. R., Vinebrooke, R. D., & Schindler, D. W. (2008). Recent climate extremes alter alpine lake ecosystems. *Proceedings of the National Academy of Sciences*, *105*(35), 12927–12931. https://doi.org/10.1073/pnas.0806481105

Pellicciotti, F., Carenzo, M., Bordoy, R., & Stoffel, M. (2014). Changes in glaciers in the Swiss Alps and impact on basin hydrology: Current state of the art and future research. *Science of the Total Environment*, *493*, 1152–1170. https://doi.org/10.1016/j.scitotenv.2014.04.022

Primicerio, R., Rossetti, G., Amundsen, P.-A., & Klemetsen, A. (2007). Impact of climate change on Arctic and Alpine lakes: Effects on phenology and community dynamics. In J. B. Ørbæk, R. Kallenborn, I. Tombre, E. N. Hegseth, S. Falk-Petersen, A. H. Hoel (Eds), *Arctic alpine ecosystems and* *people in a changing environment* (pp. 51–69). Springer. https://doi.org/10.1007/978-3-540-48514-8_4

Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T. J., Kidd, K. A., MacCormack, T. J., Olden, J. D., Ormerod, S. J., Smol, J. P., Taylor, W. W., Tockner, K., Vermaire, J. C., Dudgeon, D., & Cooke, S. J. (2019). Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, *94*(3), 849–873. https://doi.org/10.1111/brv.12480

Romeo, R., Grita, F., Parisi, F., & Russo, L. (2020). *Vulnerability of mountain peoples to food insecurity: Updated data and analysis of drivers*. UNCCD.

Sabatier, P., Poulenard, J., Fanget, B., Reyss, J.-L., Develle, A.-L., Wilhelm, B., Ployon, E., Pignol, C., Naffrechoux, E., & Dorioz, J.-M. (2014). Long-term relationships among pesticide applications, mobility, and soil erosion in a vineyard watershed. *Proceedings of the National Academy of Sciences*, *111*(44), 15647–15652.

Tonkin, J. D., Poff, N. L., Bond, N. R., Horne, A., Merritt, D. M., Reynolds, L. V., Olden, J. D., Ruhi, A., & Lytle, D. A. (2019). Prepare river ecosystems for an uncertain future. *Nature*, *570*, 301–303.

van Vliet, M. T. H., Franssen, W. H. P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P., & Kabat, P. (2013). Global river discharge and water temperature under climate change. *Global Environmental Change*, *23*(2), 450–464. https://doi.org/10.1016/j.gloenvcha.2012.11.002

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, *3*(11), 917–928. https://doi.org/10.1038/s41893-020-0559-9

Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555–561. https://doi.org/10.1038/nature09440

Woodward, G., Perkins, D. M., & Brown, L. E. (2010). Climate change and freshwater ecosystems: Impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B-Biological Sciences*, *365*(1549), 2093–2106. https://doi.org/10.1098/rstb.2010.0055

Wriedt, G., & Bouraoui, F. (2009). *Towards a general water balance assessment of Europe*. Joint Research Centre—Institute for Environment and Sustainability.

Wu, J., Huang, J., Han, X., Gao, X., He, F., Jiang, M., Jiang, Z., Primack, R. B., & Shen, Z. (2004). The three gorges dam: An ecological perspective. *Frontiers in Ecology and the Environment*, *2*(5), 241–248. https://doi.org/10.1890/1540-9295(2004)002[0241:TTGDAE]2.0.CO;2

Zarfl, C., Berlekamp, J., He, F., Jähnig, S. C., Darwall, W., & Tockner, K. (2019). Future large hydropower dams impact global freshwater megafauna. *Scientific Reports*, *9*(1), 1–10. https://doi.org/10.1038/s41598-019-54980-8

Zarrineh, N., Abbaspour, K. C., & Holzkämper, A. (2020). Integrated assessment of climate change impacts on multiple ecosystem services in Western Switzerland. *Science of the Total Environment*, *708*, 135212. https://doi.org/10.1016/j.scitotenv.2019.135212

Zhu, X., Zhang, G., Yuan, K., Ling, H., & Xu, H. (2018). Evaluation of agricultural water pricing in an irrigation district based on a Bayesian network. *Water*, *10*(6), 768. https://doi.org/10.3390/w10060768

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