

Supplementary information

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

Morgane Brosse^{1, 2}, Simon Benateau^{1, 2, 3}, Adrien Gaudard^{4, †}, Christian Stamm⁴, and Florian Altermatt^{1, 2, *}

¹*Department of Aquatic Ecology, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland*

²*Department of Evolutionary Biology and Environmental Studies, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*

³*Centre for Ecology and Sciences of Conservation (CESCO UMR7204), MNHN, CNRS, 57 rue Cuvier, 75005 Paris, France*

⁴*Department Environmental Chemistry, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland; † Deceased.*

* Corresponding author: florian.altermatt@eawag.ch

1. DIRECT EFFECTS OF CLIMATE CHANGE ON WATERBODIES

The effects of climate change through natural pathways, that is, directly related to changing climatic drivers are henceforth referred to as “direct effects”. These have multiple influences on liquid and solid waterbodies, as summarized in Figure 1. Here, we briefly synthesize the main direct effects of climate change on different elements of the hydrological cycle and different waterbodies.

Effects on air temperature and precipitation

The most pronounced effect of anthropogenic climate change is warming, causing an increase of average air and water temperature (IPCC, in Press). Furthermore, it results in a worldwide increase in the frequency and intensity of temperature extremes and heavy precipitation. About 18 % of the precipitation extremes and 75 % of the hot extremes worldwide are attributable to global warming (Fischer & Knutti, 2015). This trend is generally more intense in mountainous environments, as evidenced in the European Alps (Brunetti et al., 2009). Seasonality in alpine regions is also expected to change with a precipitation shifts from summer to winter (Freychet et al., 2017), and a change toward less snow and more rain in winter (Freychet et al., 2017). Together, this has direct effects on the temperature and hydrology regime of freshwater systems.

Effects on the cryosphere

Due to global warming, alpine ice cover is shrinking. For example, the European Alps have already lost about 50 % of the ice volume since 1900, and further shrinking of glacier and snow is predicted in the future (Pellicciotti et al., 2014). Glacier lines shift to higher latitude, timing of discharge maxima are offset, runoff regimes transform from nival to pluvial and their seasonality is redistributed (Beniston et al., 2018). Increasing runoff is expected for the next decades, followed by a decrease, because shrunken glaciers will no longer sustain runoff (see Beniston et al., 2018 and Pellicciotti et al., 2014 for a catalogue of the current and future states of the European cryosphere). The disappearance of glaciers increases the risk of glacial lake outburst flood hazard, but also creates new habitats, such as new glacier-fed lakes and increasing the length and number of rivers (Robinson et al., 2014; Wang et al., 2015), some of them may act as refugia for freshwater organisms (Ebersole et al., 2020). In alpine regions, permafrost is thawing worldwide and its disappearance will affect mass movements, sediments flux, methane release, water resource availability and vegetation in ways that are still poorly understood (Beniston et al. 2018), but that likely have direct effect on the chemistry, temperature and nutrient loading of alpine streams (Boix Canadell et al., 2019).

Effects on liquid waterbodies

Rivers. Climate change affects hydrological and thermal regimes of rivers and water temperature rises are exacerbated by declines in flowrates. Studies suggest that the worldwide mean of river temperature could increase by 1 to 2 °C in the next decades (van Vliet et al., 2013). The effects of the modified precipitation, runoff regime and seasonality also have a strong influence on water availability, the intensity of low- and high-water events and on erosion and transport of sediments. In summer, low-water events are likely to occur in most rivers and droughts will be more intense (IPCC, in Press), making intermittent and temporary streams more common (Datry et al., 2014). Reduced flow-rate and high water temperature induce lower concentrations of dissolved oxygen (van Vliet et al., 2013), with consequences on aquatic communities. A number of studies also suggest a tendency toward stronger floods (Hirabayashi et al., 2013).

Lakes. Lake summer surface temperature has already increased at a mean worldwide rate of 0.34 °C/decade from 1985 to 2009 (O'Reilly et al., 2015). This warming directly leads to stronger stratification of lake bodies and increase evaporation, resulting in eutrophication and anoxia at deep zones, affecting water security, diversity and economy (O'Reilly et al., 2015). Climate change also affects mixing regimes worldwide, with a trend toward less frequent mixing (Råman Vinnå et al., 2018). Studies in the European Alps show that this pattern may be reversed upon a rare strong winter allowing for full circulation (Råman Vinnå et al., 2018). Hence not only the extent of stratification but also the interannual variability may be strongly affected with potential consequences for many biological processes. Direct effects of this warming are increase of toxic algal blooms and methane emissions during the next decades (O'Reilly et al., 2015; Pomati et al., 2017).

Groundwater. Variation in precipitations, evapotranspiration and snow melt influence groundwater recharge and formation (Kløve et al., 2014). Studies estimate that groundwater temperature, especially by river-fed aquifers, could increase by several degrees in the next decades, causing a decrease in the oxygen content and enhancing temperature-dependent chemical processes such as redox reactions, with consequences on biogeochemical processes, fate and transport of chemicals (Kløve et al., 2014).






































| | |  increase  decrease  little or no change | Winter | Summer |
|-----------------------|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Fate processes | Mineralization | |  |  |
| | Nutrient uptake | |  |  |
| | Degradation | |  |  |
| Transport | Surface runoff | |  |  |
| | Erosion | |  |  |
| | Leaching | |  |  |
| Rivers | Temperature | |  |  |
| | Flow quantity | |  |  |
| | Flow intermittency | |  |  |
| | Dilution factor | |  |  |
| Lake | Temperature | |  |  |
| | Eutrophication | |  |  |
| | Nutrient concentrations | |  |  |
| | Deep water oxygen content | |  |  |
| Groundwater | Temperature | |  |  |
| | Recharge rate | |  |  |
| | Oxygen content | |  |  |

Figure 1. Qualitative summary of the direct effects of climate change on water quality and hydrological processes and water quality in alpine and pre-alpine settings. Effect direction (increase, decrease, or no change) are separately given for the winter and summer season. The effect direction is based on a summary of an extensive literature review by Benateau et al. (2019), and its methodology and references are detailed in the supplementary material.

2. CONSTRUCTION OF FIGURE 2

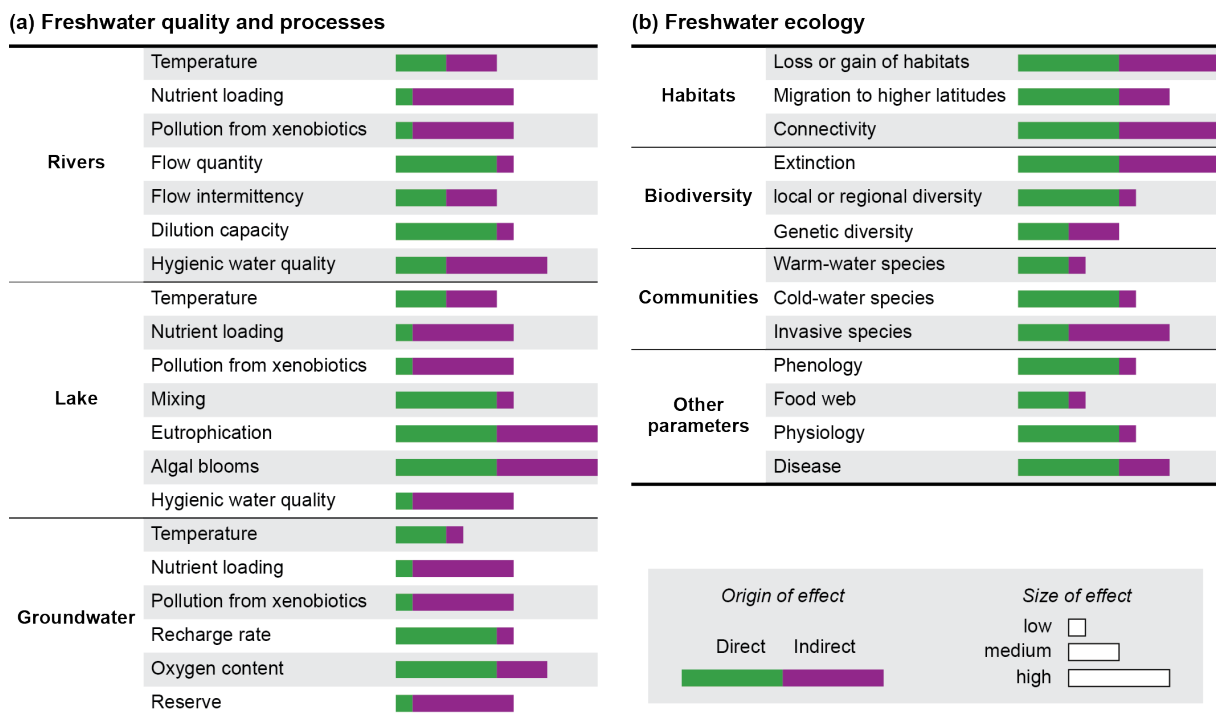


Figure 2. Qualitative summary of direct and indirect effect size of climate change on freshwater systems. (a) Effects on water quality and processes. (b) Effects on ecosystems. Figure based on data synthesized in (Benateau et al., 2019).

Studies addressing the interactions between direct and indirect effects of climate change and their impacts on freshwater systems mostly focus on few drivers/effects (Brucet et al., 2013; Condie et al., 2012; Irz et al., 2008). Growing evidences suggest an additive or even synergistic effect (Benateau et al., 2019; Mantyka-Pringle et al., 2014), but relative impacts of the direct effects and indirect effects are difficult to predict and are still poorly understood. The data and trends used in figure 2 are reflecting our interpretation of qualitative impacts only. For each of the identified categories/Phenomena, we did a qualitative assessment of the relevance of direct and indirect effects of climate change on both freshwater quality and processes as well as on freshwater ecology. We assessed effect size in three categories “low”, “medium”, and “high”. The weighing was compared across themes, such that an ordinal grouping and comparison across themes can be done, but without an exact quantification. The qualitative ordering should both show possible causes of effects, but also help to identify areas of mitigations. This figure is adapted from Benateau et al. (2019; fig. 15.1), which was partly built with individual interviews and discussions with experts on the various topics (for details, see (Benateau et al., 2019). The following other studies were used to complete this figure:

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