Chapter 11
Climate Change Impacts in Riverine Ecosystems

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11.1 Introduction

The unprecedented rates of warming observed during recent decades exceed natural variability to such an extent that it is widely recognized as a major environmental problem not only among scientists. The role of our economy in driving such change has made it an economic and political issue. There is ample evidence that climate characteristics are changing due to greenhouse gas emissions caused by human activities. As a source of extreme, unpredictable environmental variation, climate change represents one of the most important threats for freshwater biodiversity (Dudgeon et al. 2006; Woodward et al. 2010).

The Intergovernmental Panel on Climate Change (IPCC), a scientific intergovernmental institution, documents knowledge on climate change research since 1988. The last assessment report (Hartmann et al. 2013) noted the following significant trends: The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere. The observed increase in global average surface temperature from 1951 to 2010 is extremely likely to have been caused by anthropogenically induced greenhouse gas (GHG) emissions. This is underpinned by the fact that the best estimate of the human-induced contribution to warming is

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similar to the observed warming. Since 1950, high-temperature extremes (hot days, tropical nights, and heat waves) have become more frequent, while low-temperature extremes (cold spells, frost days) have become less frequent (EEA 2012). Since 1950, annual precipitation has increased in Northern Europe (up to +70 mm/decade) and decreased in parts of Southern Europe (EEA 2012). Hence, climate change is arguably the greatest emerging threat to global biodiversity and the functioning of local ecosystems.

Climate is an extremely important driver of ecosystem processes in general, but especially so in freshwater ecosystems as thermal and hydrological regimes are strongly linked to climate. Atmospheric energy fluxes and heat exchange strongly influence river water temperature, which is one of the most important factors in the chemo-physical environment of aquatic organisms (Caissie 2006). Besides temperature, climate directly affects runoff through the amount and type of precipitation. Increasingly, rising trends of surface runoff have been driven by more frequent episodes of intense rainfall. All river flow derives ultimately from precipitation, although geology, topography, soil type, and vegetation can help to determine the supply of water and the pathways by which precipitation reaches the river channel (Poff et al. 1997).

Riverine ecosystems are particularly vulnerable to climate change because (1) many species within these habitats have limited dispersal abilities as the environment changes, (2) water temperature and availability are climate-dependent, and (3) many systems are already exposed to numerous human-induced pressures (Woodward et al. 2010). Aquatic organisms such as fish and macroinvertebrates are ectothermic. Hence, they are directly and indirectly dependent on the surrounding temperatures. Climate conditions affected species distributions already in the past. Species richness patterns across Europe can still be linked to the Last Glacial Maximum with the highest species richness in Peri-Mediterranean and Ponto-Caspian Europe (Reyjol et al. 2007).

The ecological consequences of future climate change in freshwater ecosystems will largely depend on the rate and magnitude of change related to climate forcing, i.e., changes in temperature and streamflow. These changes not only imply absolute changes (increases or decreases) but also the increasing variation between extremes. The hydrological and thermal regimes of rivers directly and indirectly trigger different ecological processes. In the following section, we discuss water temperature and related processes in more detail. General principles of river hydrology are discussed in Chap. 4.

11.2   Water Temperature

Water temperature is, among others, one of the most important habitat factors in aquatic ecosystems, perhaps even the master variable (Brett 1956). Riverine fish and macroinvertebrates are ectothermic organisms, and thus, all life stages are dependent on their ambient temperatures. Generally, many factors are involved in the formation of water temperature. According to Caissie (2006), the factors, which drive the
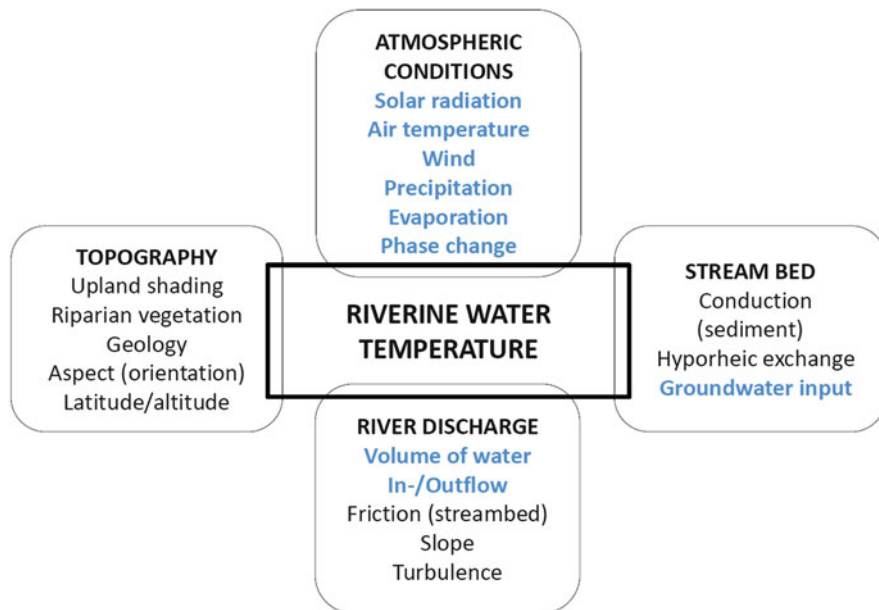
Fig. 11.1 Four groups of factors influencing the water temperature in rivers and factors that are strongly related to the climatic conditions (in blue), thus impacted by climate change (adapted after Caissie 2006)

thermal regime, can be summarized in four groups (Fig. 11.1): (1) atmospheric conditions, (2) stream discharge, (3) topography, and (4) streambed. The atmospheric conditions are highly important and mainly responsible for heat exchange processes occurring at the water surface. Topography covers the geographical setting, which in turn can influence the atmospheric factors. Stream discharge mainly determines the volume of water flow, i.e., affecting the heating capacity. Consequently, smaller rivers exhibit faster and more extreme temperature dynamics because they are more vulnerable to heating and to cooling due to lower thermal capacity. Lastly, streambed factors are related to hyporheic processes. Heat exchange processes, which are highly relevant for water temperature modeling, mainly occur at the interfaces of air and water as well as water and streambed. The former is mainly triggered by solar radiation, long-wave radiation, evaporative heat fluxes, and convective heat transfer. The contribution of other processes, such as precipitation or friction, is small in comparison. Several studies have highlighted the importance of radiation in the thermal regime. This implies the importance of riparian vegetation, which protects a stream against excessive heating (Caissie 2006).

Thermal regimes of rivers show some general trends: Water temperature increases nonlinearly from the river source to its mouth, at which the increase rate is greater for small streams than for large rivers. This general, large-scale pattern is counteracted by small-scale variabilities occurring at confluences with tributaries, in deep pools, or at groundwater inflows. While water temperature is relatively uniform
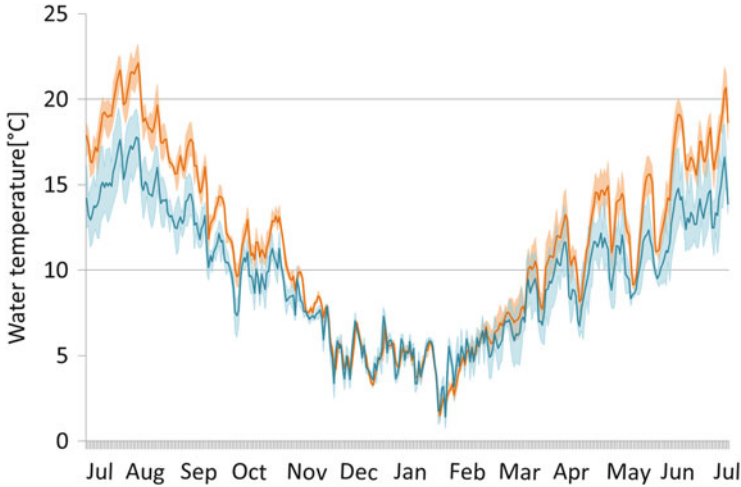
Fig. 11.2 Mean daily temperatures (solid lines) and min/max range (shaded) in the upstream (distance to source 20 km; orange) and downstream (distance to source 70 km; turquoise) section of the river Pielach, a river of the Alpine foothills in Austria

in cross sections, streams and rivers are turbulent systems where stratification is generally not expected. However, groundwater intrusion and hyporheic water exchange in pools can create cold water spots (Caissie 2006).

Besides spatial variations, the thermal regime shows temporal fluctuations of water temperature in diel and annual cycles. Daily minimum temperatures can be observed in the morning hours and maximum temperatures in the late afternoon. The magnitude of daily variations differs on the longitudinal gradient of rivers (Fig. 11.2).

Water temperature is a central feature in the chemo-physical environment of ectotherm aquatic organisms. Temperature controls almost all rate reactions (chemical and biological) and is thus a strong influence on biological systems at all levels of organization directly and indirectly triggering a magnitude of processes in aquatic life (Woodward et al. 2010). The biological dependences of the aquatic fauna and the according responses due to changes in the thermal regime are discussed in more detail below. General impacts of hydrological regimes on freshwater fauna are described in Chaps. 4, 5, and 6 allowing for the inference of potential climate change impacts.

11.3 Impacts

Riverine ecosystems are among the most sensitive to climate change because they are directly linked to the hydrological cycle, closely dependent on atmospheric thermal regimes, and at risk from interactions between climate change and existing,
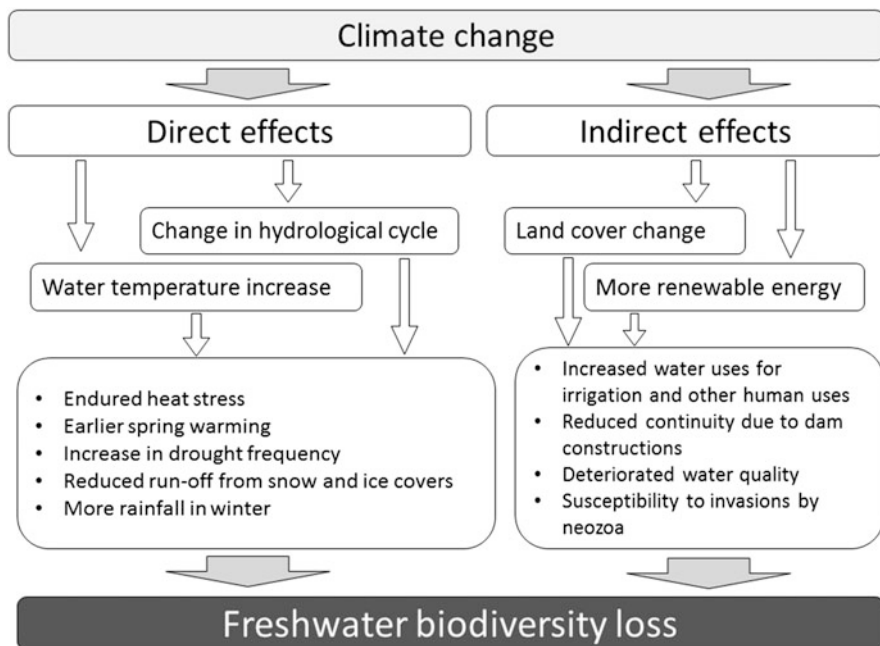
Fig. 11.3 Conceptual description of direct and indirect climate change effects on freshwater biodiversity in rivers (adapted after Fenoglio et al. 2010)

multiple, anthropogenic stressors (Dudgeon et al. 2006; Ormerod 2009). Figure 11.3 conceptually summarizes direct and indirect effects of climate change, combining hydrology and temperature. Water temperature has received much less attention with respect to ecological effects than other facets of water quality, such as eutrophication, suspended sediments, and pollution. The following section highlights climate change impacts on thermal as well as hydrological regimes. Furthermore, the interactions of climate change with other pressures are shortly discussed. Finally, this chapter addresses the ecological implications of climate change.

11.3.1   Climate Change Impacts on Thermal Regimes

An increase in air temperature will directly translate into warmer water temperatures for most streams and rivers. This change in thermal characteristics fundamentally alters ecological processes. Even though over the past 30 years warming in rivers and streams is consistently reported from global to regional scales (e.g., Webb and Nobilis 1995; Kaushal et al. 2010; Orr et al. 2014), climate change is not in all cases the exclusive reason for this warming. Temporal trends in thermal regimes can be also influenced by human-induced pressures such as impoundment, water abstraction, warm-water emissions from cooling and wastewater discharges, land use

change (particularly deforestation), or river flow regulation. However, these other causes for river warming are hard to quantify (Kaushal et al. 2010).

At many sites, long-term increases in the water temperatures of streams and rivers typically coincided with increases in annual mean air temperatures. Warming trends also occur in rivers with sparsely settled catchments with intact forest cover. A comprehensive study by Orr et al. (2014) comprising 2773 sites across the United Kingdom showed warming trends (0.03 °C per year) from 1990 to 2006, which are comparable to those reported for air temperature. Similarly, Markovic et al. (2013) showed increasing temperature trends for the Elbe and Danube rivers, which accelerated at the end of the twentieth century. Furthermore, seasonal shifts were indicated by earlier spring warming and an increase in the duration of summer heat phases. During the next century, global air temperatures are projected to increase by 1.5–4.5 °C (Hartmann et al. 2013). This temperature increase will have manifold consequences for aquatic fauna, which are discussed in more detail in Sect. 11.3.4.

Another important, human-induced impact that directly affects water temperature and thermal regimes is deforestation and removal of riparian vegetation. The removal of riparian vegetation can have tremendous effects on water temperatures as increased energy input from radiation induces heating. Small streams with lower heat capacity are quite vulnerable to this impact, especially where a full canopy of riparian vegetation naturally occurs.

11.3.2 Climatic Aspects in Hydrology

Despite the strongly consistent pattern of hydrological change in some regions, e.g., reduced runoff during summer and more runoff during winter due to shifts from snow to rainfall, there is considerable uncertainty in how climate change will impact river hydrology. In Europe, already dry regions such as the Mediterranean area or the Pannonian lowlands will become drier, and already wet regions such as Scandinavia or the Alps will become a bit wetter.

However, streamflow trends must be interpreted with caution because of confounding factors, such as land use changes, irrigation, and urbanization. In regions with seasonal snow storage such as in the Alps, warming since the 1970s has led to earlier spring discharge maxima and has increased winter flows due to more precipitation as rainfall instead of snow. Moreover, where streamflow is lower in summer, decrease in snow storage has exacerbated summer dryness.

The projected impacts in a catchment under future climate conditions depend on the sensitivity of the catchment to change in climatic characteristics and on the projected change of precipitation, temperature, and resulting evaporation. Catchment sensitivity is a function of the ratio between runoff and precipitation. Accordingly, a small ratio indicates a higher importance of precipitation for runoff. Proportional changes in average annual runoff are typically between one and three times as large as proportional changes in average annual precipitation (Tang and Lettenmaier 2012). In turn, the smaller the ratio, the greater the sensitivity. However, the uncertainties in the hydrological models can be substantial. In some regions and especially on

medium time scales (up to the 2050s), uncertainties in hydrological models can be greater than climate model uncertainty, i.e., uncertainty in the results of the hydrological model is larger than the predicted change induced by altered climate conditions and thus having no significant meaning.

In alpine regions, glaciers can contribute appreciable amounts of water to the discharge of rivers. All projections for the twenty-first century show continuing net mass loss from glaciers. In glaciered catchments, runoff reaches an annual maximum during summer, which strongly influences river thermal conditions as well. Reduced contributions from glacial runoff induce shifts of peak flows toward spring. Furthermore, the reduced glacial input can lead to more erratic and variable discharge dynamics in response to rain events. The relative importance of high-summer glacier meltwater can be substantial, for example, contributing 25% of August discharge in basins draining the European Alps (Huss 2011). Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases. In the first phase, river discharge increases due to intensified melting. In the second phase, snowfields melt early and glaciers have shrunken to a point that late-summer streamflow is strongly reduced. The turnover between the first and second phase is called "peak meltwater." Peak meltwater dates have been projected between 2010 and 2040 for the European Alps (Huss 2011).

River discharge also influences the response of thermal regimes to increased air temperatures. Simulated discharge decreases of 20 and 40% may result in additional increases of river water temperature of 0.3 and 0.8 °C on average (Van Vliet et al. 2011). Consequently, where drought becomes more frequent, freshwater-dependent biota will suffer directly from changed flow conditions and also from drought-induced river temperature increases. Furthermore, increased temperature will accompany decreased oxygen and increased pollutant concentrations.

Hydrology itself is a driver of aquatic communities, and disturbances, such as floods, have regulatory effects on riverine biota as dominant populations are reduced, pioneers are supported, and free niches are opened. Hydrological dynamics are therefore essential to maintain overall biodiversity in aquatic ecosystems. Riverine species have evolved specific life-cycle adaptations to seasonal differences in hydrological regimes that are specific to different eco- and bioregions. For instance, larval growth rates of benthic invertebrates are high during winter as the hydraulic stress is reduced in low-flow periods in alpine rivers. Disturbances, such as acyclic extreme events, may be linked with severe losses in biomass, with species richness, and with the selection of species-specific traits. Unstable environments favor small, adaptive species with short life cycles, whereby larger organisms with longer life spans are generally handicapped (Townsend and Hildrew 1994; see Chap. 4).

11.3.3   Interactions of Climate Change with Other Stressors

Climate change is not the only source of stressors impacting water resources and aquatic ecosystems. Non-climatic drivers such as population increase, economic development, pollutant emissions, or urbanization challenge the sustainable use of

resources and the integrity of aquatic ecosystems (Dudgeon et al. 2006; Nelson et al. 2006). Changing land uses are expected to affect freshwater systems strongly in the future: Increasing urbanization and deforestation may decrease groundwater recharge and increase flood hazards with consequences for hydrology. Furthermore, agricultural practices are strongly related to the climatic conditions (Bates et al. 2008). Thus, agricultural land use will be of particular importance for the integrity of freshwater systems in the future (see Chap. 13). Irrigation accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll 2009).

Climate can induce change in human uses or directly interact with human pressures. Hydropower generation, for example, causes major pressures on riverine ecosystems. Through damming, water abstractions, and hydropeaking, hydropower plants affect habitat quality by, e.g., altering river flow regimes, fragmenting river channels, or disturbing discharge regimes on hourly time scales (Poff and Zimmerman 2010) (for more details, see Chaps. 4–7). However, climate change affects hydropower generation itself through changes in the mean annual streamflow, shifts of seasonal flows, and increases of streamflow variability (including floods and droughts) as well as by increased evaporation from reservoirs and changes in sediment fluxes. Some of these interactions can have negative effects on hydropower generation as well. Especially, run-of-the-river power plants are more susceptible than storage-type power plants to climate change impacts, such as increased flow variability. However, the existing pressures of hydropower generation can be augmented by climate change; e.g., low-flow conditions in river reaches downstream of diversion power plants may be amplified through drought.

Another important field of interacting effects is water quality. On the one hand, increased water temperatures influence many biogeochemical processes such as the self-purification of water. On the other hand, rising temperatures will lead to increasing water demands by socioeconomic systems (e.g., for irrigation or cooling). Water quality aspects are discussed in more detail in Chap. 10.

11.3.4 Ecological Impacts of Thermal Regimes on Aquatic Fauna

As discussed above, climate change will affect several ecosystem processes relevant for aquatic life. The most pervasive impact of climate change will be the change of the thermal regime and mostly a warming of water temperatures. Therein, climate change will affect several characteristics of the thermal regime (e.g., mean, minima, and maxima), which are relevant for aquatic life.

Almost all fishes and macroinvertebrates are obligate poikilotherms or thermal conformers; as such, almost every aspect of the ecology of an individual is influenced by the temperature of the surrounding water from the egg to the adult individual (Brett 1956). Fry (1947) outlined five main categories of temperature

effects on fishes that are likely to influence macroinvertebrates too: controlling (metabolic and developmental rates), limiting (affecting activity, movement, and distribution), directing (stimulating an orientation response), masking (blocking or affecting the expression to other environmental factors), and lethal effects that act either directly to kill the organism or indirectly as a stress effect. Thus, the responses of the aquatic fauna to water temperature changes might occur at various levels of organization from the molecular through organismal and population to the community level (McCullough et al. 2009; Woodward et al. 2010). Climate and thus climate change can affect almost every component of an individual fish's life including availability and suitability of habitats, survival, reproduction, and successful hatching, as well as metabolic demands. The temperature thresholds associated with these effects differ not only between species but also between different life stages. Besides the different organizational levels, the responses of aquatic fauna to climate change will be heterogeneous due to regional and taxonomic variations. In the following, the different organizational levels will be discussed and related to climate change impacts with a focus on the population (including species) and community level.

At the molecular level, the thermal tolerance of an organism and its physiological limits are key determinants as to whether the organism is able to adapt to the thermal conditions due to its genetic constitution. Biological reactions to impacts on the molecular level include heat shocks, stress responses, and changes to enzyme function or to genetic structure. However, the physiological response of an organism is also linked to other parameters, such as sex, size, season, and water chemistry. Thus, the thermal preference of a species cannot adequately be described by a single temperature value, such as the mean. Several metrics can be used to quantitatively describe the thermal preference and tolerance of a species and its life stages: optimum growth temperature supporting the highest growth rate, final temperature preference indicating the temperature toward which a fish tends to move when exposed to a temperature range, upper incipient lethal limit, the upper temperature value that 50% of fish survive in an experiment for an extended period, critical thermal maximum that describes the upper temperature in an experiment at which fish loses its ability to maintain the upright swimming position, optimum spawning temperature, and optimum egg development temperature. Actually, lethal temperatures relate not only to a fixed maximum threshold. The maximum temperature a species or a specific life stadium withstands is also strongly related to the acclimation time, i.e., the time over which temperature changes.

According to Magnuson et al. (1997), aquatic organisms can be classified into three thermal guilds: (1) cold-water species with physiological optimums <20 °C, (2) coolwater species having their physiological optimums between 20 and 28 °C, and (3) warm-water species with an optimum temperature > 28 °C. Even though it is possible to delineate thermal niches in the laboratory, evidence from field data is much more heterogeneous (Magnuson et al. 1979) as in complex and dynamic river systems the interplay of several biotic and abiotic factors is relevant for the aquatic organisms.

At the organismal level, fish are able to react behaviorally to stay within the range of their thermal tolerance and to avoid stress effects or sublethal effects. Even though fish, as exotherms, cannot physiologically regulate their body temperature, they are

able to select thermally adequate microhabitats by movement within the range of temperatures available in their environment. Movements to avoid stressful thermal conditions and stay within adequate habitat conditions are important behavioral responses to changing spatial and temporal patterns of temperature (McCullough et al. 2009). In contrast to large-scale migrations into new habitats that will be discussed below under the population level, behavioral movements do not change the potential distribution area of a species. Such movements are temporarily limited habitat changes. Thermal stress can lead to reduced disease resistance or changed feeding and foraging, all having negative effects on the fitness and viability of the individual. By contrast, macroinvertebrates do not have the possibility for directional movements within flowing water. Macroinvertebrates have the option to retract into interstitial spaces within the bottom substrate or to drift by passive movement downstream (into warmer river reaches).

At the population level (including the species), factors relevant to responses to thermal variability are spatial distributions on the species level as well as population viability including abundance, productivity, and genetic diversity. If thermal conditions continuously exceed the preferred range of a species and adequate habitats diminish in the current environment, temporal movements into adequate microhabitats, as discussed under the organismal level, become insufficient to secure survival of the population. In this case, temperature drives changes in potential distribution area. Aquatic organisms have two options to stay within a specific thermal niche under warming environments due to climate change: either migrate to northern latitudes or to higher altitudes (see Fig. 11.4).
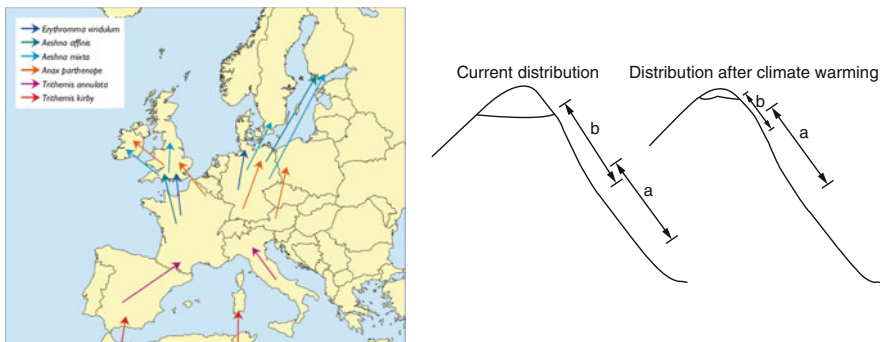

Fig. 11.4 Changes in distribution patterns due to climate change. Left: migration pathways of selected Odonata from southern to northern latitudes (Ott 2010) (reproduced from Ott J. (2010) The big trek northwards: recent changes in the European dragonfly fauna. In: Settele J., Penev L., Georgiev T., Grabaum R., Grobelnik V., Hammen V., Klotz S., Kotarac M. & Kühn I. (Eds) (2009): Atlas of Biodiversity Risk, with permission of Pensoft Publishers). Right: migration of species to higher altitudes and segregation of species groups along elevational and temperature gradients in mountainous regions currently and under climate warming. Elevational ranges of species in group b would be reduced due to displacement by the expanding ranges of species in group a (Rahel et al. 2008) (reproduced from Rahel F.J. et al. (2008) Assessing the effects of climate change on aquatic invasive species. Conservation Biology, 22, 521–33, with the permission of John Wiley & Sons. Ltd., © 2008 Society for Conservation Biology)

However, the possibility to migrate and thus the possibility to follow or to reach thermally suitable habitat depend on two criteria: firstly on the dispersal ability of the species and secondly on the availability of passable migration pathways and corridors to suitable habitats, respectively. Capacity for the former, i.e., dispersal abilities, can be measured in terms of how much time it takes a species to follow the thermal niche or how far species can follow this niche, but these are still not well investigated and largely unknown. In the latter case, migration pathways for endemic species are uncertain. Endemic species have limited distributions for several reasons. Purely aquatic species are expected to be severely challenged by climate change, especially if the river network is not connected to higher latitudes or elevations, and thus to cooler habitats. For example, fish species of the Mediterranean region, where endemism is high, may find no passable route to migrate northward in river systems draining to the Mediterranean Sea.

Another example where migration is impossible is the springs of rivers. Springs, i.e., the real source of the river, are colonized by specific species and assemblages of benthic invertebrates. These assemblages are assumed to be especially vulnerable to any environmental changes in terms of temperature or hydrology, since these habitats have "extratropical" character, i.e., the habitat conditions are and have been extremely constant over time. These assemblages and habitats are especially vulnerable in medium elevation ranges, around 1500 m, where climate-induced temperature increases will raise the source temperature of rivers. These species are among potential losers of climate change effects as they are trapped in sky islands, i.e., mountain refugia, and are not able to shift to suitable thermal or hydrological conditions, either up- or downstream (Bässler et al. 2010; Sauer et al. 2011; Dirnböck et al. 2011; Vitecek et al. 2015a, b; Rabitsch et al. 2016). Another vulnerable stream type is glacier-fed streams with cold and turbid waters inhabited by species specialized for these exceptional conditions. The shrinkage of glaciers will reduce local and regional diversity (Jacobsen et al. 2012).

Generally, the change of distribution patterns is a central topic in climate change impact research in aquatic ecosystems. Climate is a strong determinant in biogeographical distribution patterns (Reyjol et al. 2007), and hence, climate change will have huge impacts on the biogeographical configuration of aquatic communities. Comte et al. (2013) reviewed observed and predicted climate-induced distribution changes for fish. Most evidence was found for cold-water fishes and within cold-water fishes for salmonids (Fig. 11.5). This is not surprising as the different species of salmon and trout are economically highly relevant in angling and fisheries and often represent species with a high cultural value too. Nonetheless, climate change impacts are less well studied in freshwater environments than in the terrestrial or marine realm.

In most cases, climate change-induced distribution shifts of cold-water species lead to shrinking habitat availabilities due to the loss of habitats at the downstream end of the distribution area or to an upstream shift into cooler areas. Filipe et al. (2013) forecasted future distribution of trout across three large basins in Europe covering a wide range of climatic conditions. The predictions clearly showed tremendous losses of habitats. In turn, the Alps represented a stable distribution
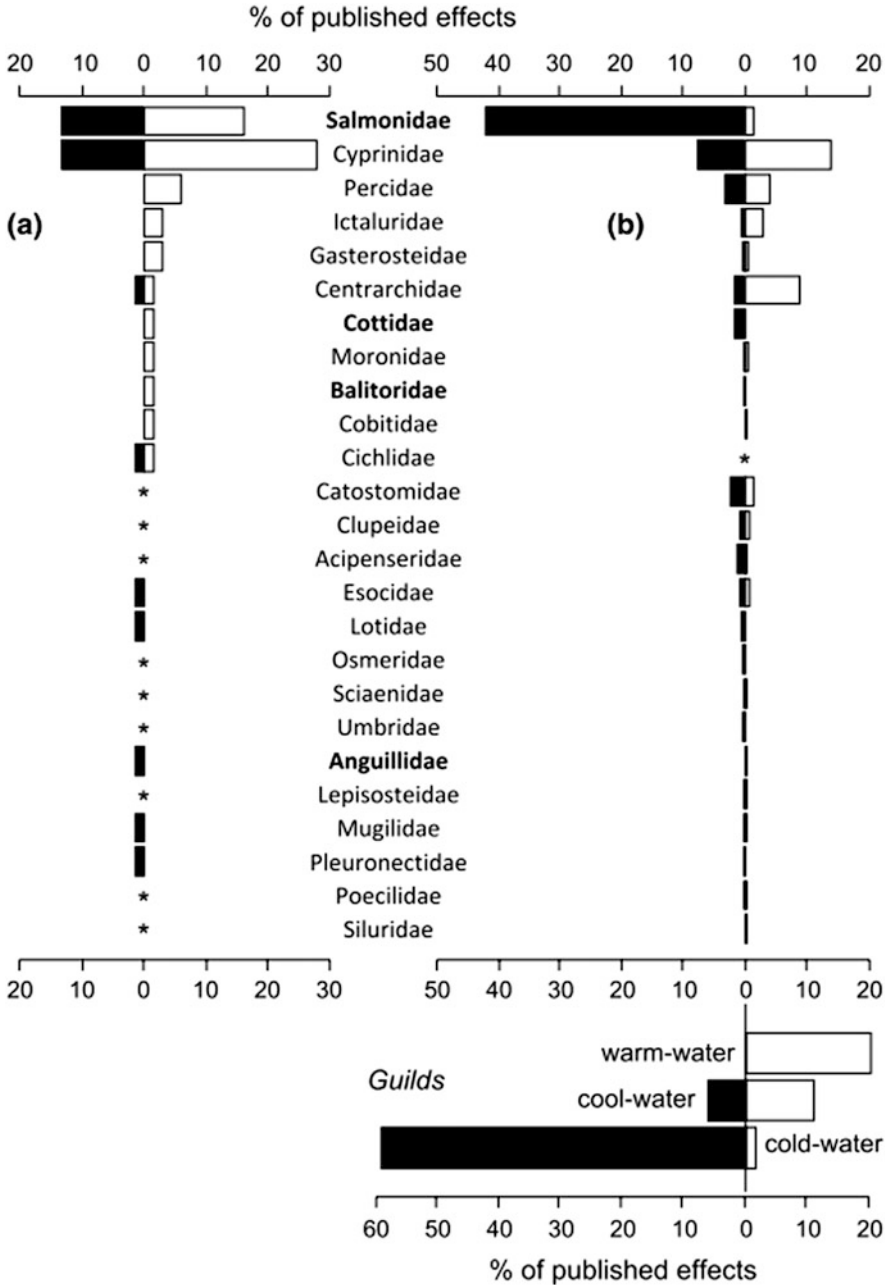
Fig. 11.5 Proportion of negative (black bars) and positive (white bars) effects reported: (**a**) observed effects and (**b**) predicted effects according to the level of biological organization for which predictions have been made (thermal guilds versus species). Asterisks indicate families of which no species has been studied. Bold indicates families for which the proportion of categorical
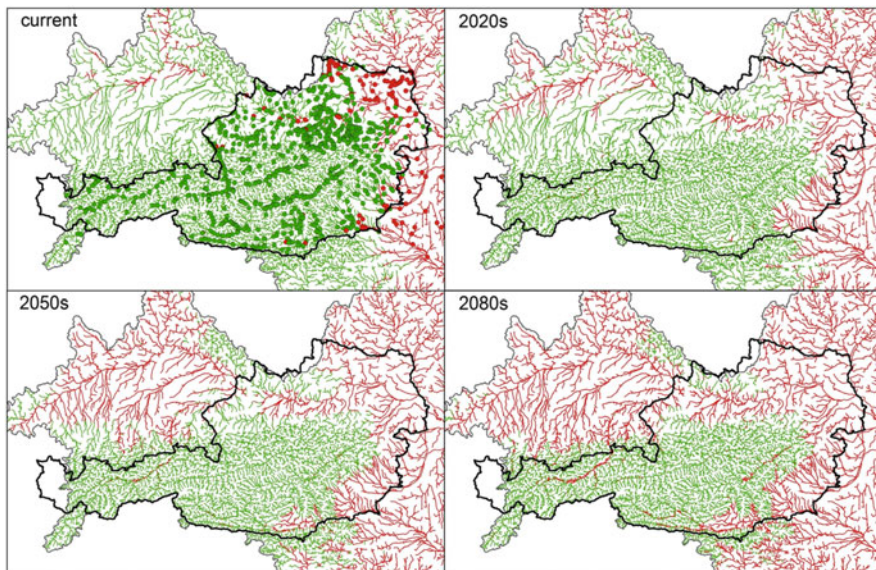
Fig. 11.6 Change of trout (*Salmo trutta*) distribution due to climate change impacts in the upper Danube Basin covering the alpine range of Austria based on the model of Filipe et al. (2013)

area in the models (Fig. 11.6). On a large-scale, continental perspective, the conservation of such habitats is highly important in the face of climate change, since the habitats will dramatically reduce in other areas. If these thermally suitable habitats and their trout populations are impacted by other pressures, the species can be also extirpated in this area. Hari et al. (2006) underlined the relationships of warming rivers in the Swiss Alps and the already occurred decline of trout populations at the end of the twentieth century.

In the case of trout, the species already occupies the upstream sections of upland rivers. Potentially in some areas, trout may extend its distribution further upstream, but in most cases, a further migration may be limited by habitat factors other than temperature or by topographical barriers, respectively. In turn, species that are currently occurring more downstream would have the possibility to track their thermal niche into upstream reaches. However, Comte and Grenouillet (2015) showed that riverine fish species consistently lagged behind the speed at which climate change gains elevation and latitude (Isaak and Rieman 2013) with higher rates for habitat losses than for habitat gains, i.e., the preferred thermal range and the

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Fig. 11.5 (continued) effects differed between the observed and predicted effects, according to binomial tests ($P < 0.05$) (Comte et al. 2013) (reproduced from Comte et al. (2013) Climate-induced changes in the distribution of freshwater fish: Observed and predicted trends. Freshwater Biology, 58, 625–639, with the permission of Wiley & Sons Ltd., © 2012 Blackwell Publishing Ltd.)

actually occupied thermal environment drift apart from each other. This lag can be also caused by insufficient connectivity that represents a highly important issue for migration but is impaired by other human-induced impacts such as barriers or also water abstraction. Macroinvertebrates may overcome the problem of migration barriers by overland (aerial) dispersal in their adult life stage, since most aquatic insects have winged adult stages. However, some of these species are poor fliers (e.g., mayflies) and would most likely not be successful to migrate upward, particularly in regions with strong winds or distinct topography.

Temperature effects on communities comprise responses to temperature via food web dynamics, interactions among fish species or biotic interactions among different taxa, as well as the role of diseases and parasites. Furthermore, the emergence of non-native, exotic species is highly relevant in community aspects. Thus, this organizational level is highly relevant with respect to biodiversity that is especially under pressure in freshwater ecosystems (Dudgeon et al. 2006). However, distribution shifts of single species as discussed under the population level are linked to the dynamics of community composition.

The transition of fish species along the river continuum is characterized by two trends: (1) downstream increase of species richness and biomass and (2) turnover in species composition from salmonid to cyprinid communities. In Europe, the species-poor assemblages of the upstream reaches are dominated by cold-water species and the downstream reaches by warm-water-tolerant species. The, in comparison with fish communities, species-rich macroinvertebrate communities change in similar fashion along the river continuum in distinct reaction to temperature and other parameters such as oxygen saturation, substrate composition, flow velocity, and food resources. Temperature increases can thus induce assemblage shifts.

Pletterbauer et al. (2015) investigated fish assemblage shifts based on the Fish Zone Index (FiZI) that considers not only the occurrence of a species but also its abundance (Schmutz et al. 2000). The results showed significant assemblage shifts across major parts of Europe with strongest impacts on fish assemblages in upstream sections of small- and medium-sized rivers as well as in Mediterranean and alpine regions. By comparing distribution shifts for different taxa groups in different regions, Gibson-Reinemer and Rahel (2015) recently found that responses are idiosyncratic for plants, birds, marine invertebrates, and mammals. The authors stated that "inconsistent range shifts seem to be a widespread response to climate change rather than a phenomenon in a single area or taxonomic group." Thus, distribution shifts will not occur for all species at the same time and to the same extent. Accordingly, vulnerabilities have to be addressed on the different levels of organization. Hering et al. (2009) analyzed the vulnerability of the European Trichoptera fauna to climate change and found that parameters such as endemism, preference for springs or for cold water temperatures, short emergence period, and restricted ecological niches in terms of feeding types are responsible for the species-specific sensitivity to climate change impacts. Accordingly, species of the Mediterranean peninsulas and mountainous areas in Central Europe are potentially more threatened than species of Northern Europe (Fig. 11.7).
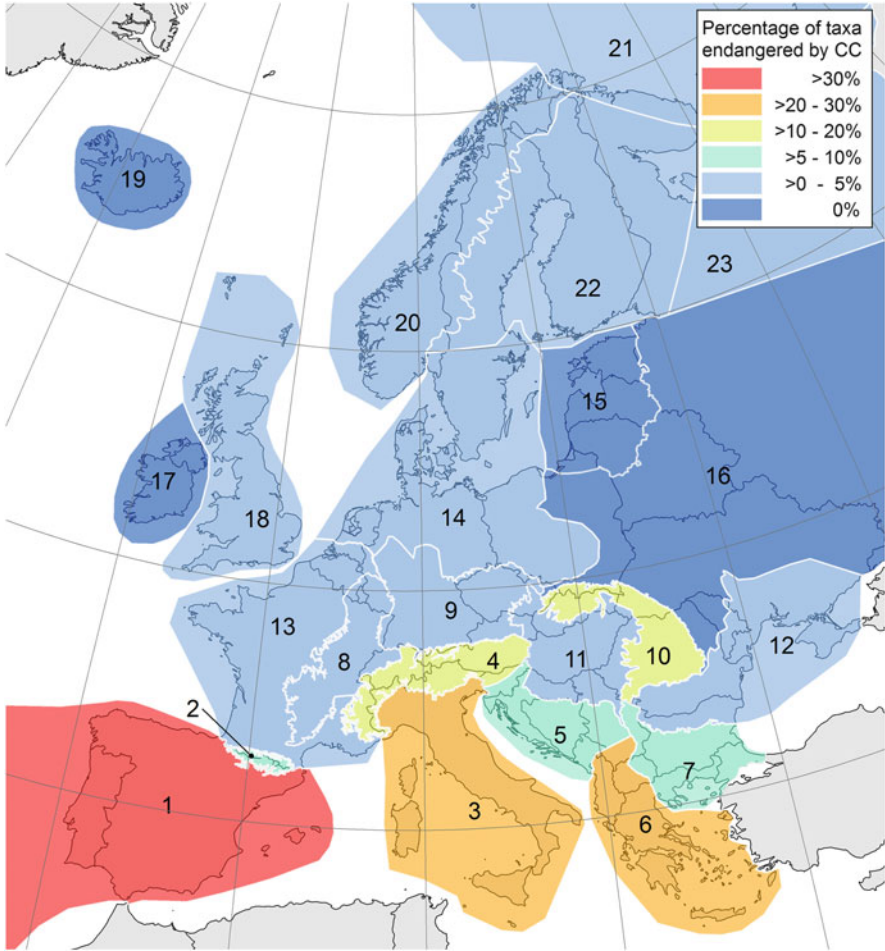
Fig. 11.7 Fraction of Trichoptera taxa potentially endangered by climate change in the European ecoregions (Hering et al. 2009), numbers indicate the Ecoregion number (© Aquatic Sciences, Potential impact of climate change on aquatic insects: A sensitivity analysis for European caddisflies (Trichoptera) based on distribution patterns and ecological preferences, 71, 2009, 3–14, Hering D., Schmidt-Kloiber A., Murphy J., Lücke S., Zamora-Muñoz C., López-Rodríguez M.J., Huber T., Graf W. With permission of Springer)

11.4   Adaptation and Restoration

Successful climate change adaptation requires responses at the appropriate temporal and spatial scales. However, sustaining integral ecosystem processes and functions will need inter- and transdisciplinary approaches to address climate change impacts. The effects of climate change are already visible and measurable in aquatic ecosystems.

Hence, conservation and restoration practitioners and researchers need to share information effectively and with diverse audiences such as policy- and decision-makers, NGOs, and other stakeholders to ensure sharing most recent findings and to enable proactive management (Seavy et al. 2009). Rapid environmental change urgently requires society to be informed about the ongoing and upcoming threats related to climate change.

Broad suggestions for adapting rivers to climate change impacts are similar to those for other ecosystems, including the enhancement of resilience, connectivity, and legal protection while reducing stressors, such as habitat degradation or fragmentation (Palmer et al. 2008). However, the development of adequate and robust management strategies is key to conserve intact, freshwater habitats. With respect to climate change and aquatic ecosystems, water temperature is one of the master variables that requires attention.

Riparian vegetation contributes various important functions in relation to aquatic habitats, including the moderation of water and ambient air temperature via evapotranspiration and reduction of solar energy input by shading. It thus provides a buffer zone that filters sediments and nutrients, provides food, and creates woody debris as habitat for xylobiont species (Richardson et al. 2007). Evapotranspiration rates are highest in forest habitats due to their high leaf area index (Tabacchi et al. 1998). In this context, a major issue is the mitigation potential of riparian vegetation to keep rivers cooler. Recent studies have shown that shading by riparian vegetation can buffer the warming effects of climate change (Bond et al. 2015).

Another important aspect in climate change adaptation is habitat connectivity. As discussed above, species will tend to follow their preferred thermal niche in their river network. Accordingly, the spatial connection between different river reaches is highly important, especially for cold-water taxa, as long-term thermal refugia are located upstream where water temperature is lowest along the longitudinal continuum. As shown by Isaak et al. (2015), thermal habitats in mountain streams seem highly resistant to temperature increases. As a result, many populations of cold-water species currently exist where they are well-buffered from climate change. However, connectivity is not only relevant on the scale of the river network. On shorter time scales, cold-water refugia may occur as patchy distributions along the river course. Deep pools with high groundwater exchange rates or other river sections with groundwater intrusion can provide valuable habitats where species can endure heat waves. Accordingly such refugia must be connected to the surrounding habitats such that they can be accessed and used. However, morphological degradation impedes the availability of such refugia. Thus, habitat heterogeneity and morphological integrity, including natural riverbed and sediment dynamics, are essential to provide adequate habitat patches for different species and their life stages, also from the thermal point of view.

In addition to climate change, the future of freshwater ecosystems will be strongly influenced by other sources of stress: socioeconomic and technological changes as well as demographic developments on the global scale (Dudgeon et al. 2006; Nelson et al. 2006). Ultimately, as climate change impacts start to overwhelm the capacity of society and of ecosystems to cope or adapt, substantial reduction in GHG emissions

becomes inevitable. Until some combination of foresight, technological advances, and political will makes such reduction possible, research, monitoring, and experimental advances in practice must be pursued to inform society and to slow the effects of climate change on riverine ecosystems.

11.4.1 Case Study BIO_CLIC: Potential of Riparian Vegetation to Mitigate Effects of Climate Change on Biological Assemblages of Small- and Medium-Sized Running Waters

The transdisciplinary research project BIO_CLIC investigated the impact of riparian vegetation on the water temperature regime as well as on aquatic organisms of small- and medium-sized rivers in southeastern Austria. Its objectives were to identify and understand the potential of riparian vegetation to mitigate climate change impacts on water temperature and, ultimately, on benthic invertebrate and fish species assemblages. Finally, BIO_CLIC aimed to support river managers in implementing integrative management for sustainable river restoration toward climate change adaptation that incorporates ecosystem services and socioeconomic consequences.

The study area in the Austrian lowlands, represented by the rivers Lafnitz and Pinka, was chosen, because in this area an increase of air temperature of ca. 2–2.5 °C is predicted by 2040. Moreover, climate change effects combined with a rising numbers of rivers without or with low levels of riparian vegetation will lead to an increase of water temperature. It can be assumed that climate change effects will exacerbate ecological consequences by impacting water temperature and also hydrology (e.g., increasing the incidence and duration of low-flow periods).

The river Lafnitz amply exhibits hydrologically and morphologically intact river sections with near-natural riparian vegetation. By contrast, the river Pinka is impacted by river straightening and riparian vegetation loss. Due to the spatial proximity of these two rivers, the climatic conditions are comparable, but their different hydro-morphological settings qualify them for analysis to distinguish the effect of riparian vegetation on the thermal regime as well as climate change impacts. Additionally, specific sites along the rivers Lafnitz and Pinka were analyzed according to elements influencing the biological quality of fish and benthic invertebrates, e.g., water temperature, riparian vegetation, and morphological (e.g., channelization, riverbed structure) characteristics.

The results of time series analysis show clearly the difference between the two rivers. In the upper and middle reaches, the mean July water temperature in the Pinka exceeds 15 °C, which sharply contrasts with a more flattened gradient of lower temperatures in the water column of the river Lafnitz. One key reason is the lack of shading effects by the riparian vegetation that is generally missing on the Pinka. For both rivers, water temperature and fish and benthic invertebrate distributions are highly correlated along the longitudinal gradient. This underlines the strong

influence of water temperature on the longitudinal distribution of aquatic organisms and highlights the importance of mitigation of global climate change effects by shading. Shifts of their associated species to cold and warm water within the biocenotic (fish) zones will be inevitable with increasing temperatures, forcing the cold-water species to move to higher altitudes, if river connectivity allows.

In more natural river sections with fewer human pressures, in summer months, the water temperature difference between shaded and unshaded biocenotic zones is about 2–3 °C. As temperature increases, other river characteristics such as river dimension, flow, and substrate composition, but also migration barriers, might prove to be limiting factors leading to relatively unpredictable changes in the biotic assemblages. Riparian vegetation and shading could ameliorate such threats by harmonizing and flattening maximum temperature peaks in hot periods by up to 2 °C. This is about the same range of temperature increase that was predicted as an impact of climate change effects in 2050.

Global warming has already shown impacts on European freshwater ecosystems and the services they provide to humans. The main impacts are related to biodiversity, water quality, and health: Environmental parameters specify boundary conditions for habitat availability, and likewise human-induced restraints reduce further opportunities for a dynamic, ever-changing ecosystem. The results clearly demonstrate that efficient river restoration and mitigation requires the reestablishment of riparian vegetation as well as an open river continuum and hydro-morphological improvement of habitats (Melcher et al. 2016).

11.5   Conclusions, Open Questions, and Outlook

Rivers have experienced centuries of human-induced modifications (Hohensinner et al. 2011). While climate change may already impact riverine ecosystems, in the future it is much more likely that human-induced modifications will clearly and unequivocally be accompanied by climate change effects. Consequently, the challenge of how to preserve the status quo or to get back to a more pristine status will become more difficult as fundamental ecosystem processes, such as the thermal regime, will shift. From an applied perspective, climate change has the potential to undermine many existing freshwater biomonitoring schemes, which focus mostly on human pressures like organic pollution or hydro-morphological alterations with little consideration for the increasing influence of climatic effects. Thus, how we currently assess "ecological status" could become increasingly obsolete over time, as the environmental conditions drift away from assumed earlier (and cooler) reference conditions (Woodward et al. 2010) and causal relationships underpinning ecological processes realign. Thus, we may assume that sustaining and restoring habitat heterogeneity and connectivity will continue to enhance ecosystem resilience, but it may be increasingly difficult to know how much or how fast. Long-term monitoring is essential to observe changes induced by climate that are currently lacking for biological quality elements in rivers. However, improving the research focus of

monitoring programs to directly address uncertainties raised by climate change should make data available that will better inform future management decisions. Tracking data over the long term will provide the baseline trajectories against which scenarios of simulated management policies can be compared. While surprise from climate change is inevitable, challenging simulation of policies with real data will make it more possible to project the consequences of river policies over longer time periods and to identify and respond to emerging trends in changing conditions.

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