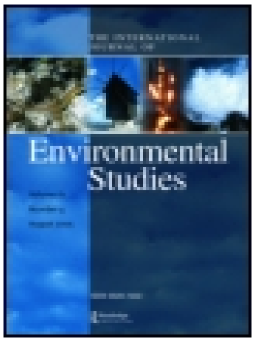

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Freshwater biodiversity: a review of local and global threats

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The total freshwater biodiversity is not fully known. In particular, freshwater invertebrates and microbes are poorly studied groups, and in tropical latitudes, that support most of the species of the world, the information is lacking. Although almost a hundred thousand of species live in fresh water, the species losses continue at the high rate and the probability of preserving much of the remaining biodiversity in fresh water seems to be very low. Freshwater ecosystems are increasingly influenced by multiple stressors that lead to loss of sensitive species and an overall reduction in diversity. Environmental change threatens freshwater biodiversity. This paper reports an extensive review of work that evaluates the current main threats for freshwater biodiversity, on a local and global scale.

Keywords: Freshwaters; Biodiversity; Rivers; Lakes; Local; Global; Threats

Introduction

Over 10,000 species of fish live in fresh water [1], approximately 40% of global fish diversity and a quarter of the world's vertebrate species. In addition, there are amphibian species, aquatic reptiles (crocodiles, turtles, etc.) and mammals (otters, river dolphins, platypus, etc.) in freshwater habitats. A third of all vertebrates are confined to freshwater. Freshwater is only 0.01% of water in the world and about 0.8% of the land surface [2], but this small fraction of the global water supports at least 100,000 species, which is almost 6% of all the described species [3]. Biodiversity of freshwater and inland waters is a valuable natural resource in economic, cultural, aesthetic, scientific and educational terms. Conservation and management is critical, but freshwater biodiversity is experiencing a decline far higher than that in the most affected terrestrial ecosystems [4]. If man's increasing demand for water continues unabated and the species losses continue at current rates, the chance of preserving much of the remaining biodiversity in freshwater will be very low (figure 1).

Although thousands of species described by scientists live in freshwater [5], an additional 50,000 to 100,000 species can live in groundwater [6]. There are insufficient data on the diversity of most groups of invertebrates in tropical freshwaters, but high levels of local endemism and species richness seem typical of several major groups, including decapod molluscs [7], crustaceans and aquatic insects [8], such as caddis [9] and mayflies

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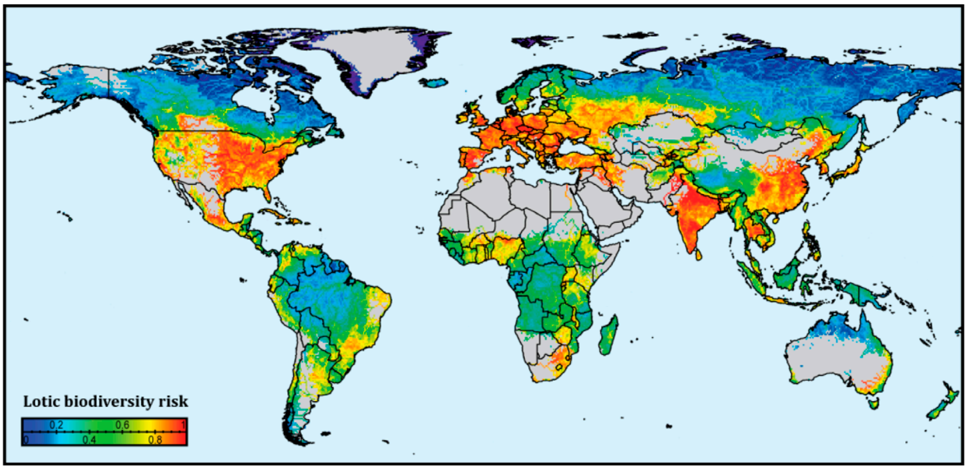

Figure 1. Biodiversity risk (from low-blue to high-red) of freshwater ecosystems.
Source: [35], adapted from [28].

[10]. Most of the prokaryotes' diversity remains unexplored [11, 12]. Moreover, it is likely that the richness of freshwater microalgae and fungi has been underestimated [13, 14].

In general, the knowledge of the total freshwater diversity is woefully incomplete, in particular between invertebrates and microbes, and especially in tropical latitudes that support most of the species of the world. Vertebrates also are not completely known, including well-studied taxa, such as the fish [15]. Between 1976 and 1994 an average of 309 new species of fish annually, about 1% of known fish, have been formally described or resurrected from synonymy [16], and this trend continues [1]. Among the amphibians, nearly 35% of the 5778 species have been described over the last decade [17].

This paper reports a comprehensive review of published studies that qualitatively and quantitatively examine the current threats to biodiversity on a local and global scale.

Local threats for freshwater biodiversity

Freshwater ecosystems are increasingly impacted by multiple stressors that lead to a loss of sensitive species and an overall reduction in diversity [18]. Threats to global freshwater biodiversity can be grouped under seven interacting categories: overexploitation; water pollution; flow modification; destruction or degradation of habitat; invasion by exotic species; and hydropower [19]. Climate change, occurring at the global scale, together with nitrogen deposition, and runoff patterns [20] are superimposed threats upon all of the previous categories.

Over-exploitation and habitat degradation

Over-exploitation affects mainly vertebrates, mostly fish, reptiles and some amphibians, while other impacts have consequences for the whole biodiversity of freshwater from microbes to megafauna.

Pollution problems are pandemic [3], and although some industrialized countries have made considerable progress in reducing water pollution from domestic and industrial point sources, the threats from excessive nutrient enrichment [21] and other chemicals, such as endocrine disruptors, are growing [22]. Habitat degradation is caused by a number of interacting factors [3]. It may involve direct effects on the aquatic environment (such as the excavation of river sand) or indirect impacts that result from changes within the drainage basin (table 1). For example, deforestation is usually associated with changes in surface runoff and increased river sediment loads that can lead to habitat alterations, such as coastal erosion, choking of coastal habitats, clogging of river bottoms and alluvial aggradation [3].

Flow changes and water pollution

Flow changes are ubiquitous in running waters [23, 24]. These vary in severity and type, but tend to be more aggressive in regions with highly variable flow regimes. This is because human beings in these places have the greatest need for protection against flooding or water conservation. The fact that existing dams retain about 10,000 km^3 of water, five times the equivalent of the volume of all rivers of the world [25], illustrates the global level of human alteration of river flow. Impoundment of water from dams in the northern hemisphere is now so great that it has caused measurable geodynamic changes in rotation and gravitational field of the Earth [26]. Even some of the largest rivers in the world now run dry for part of the year or are flowing partially dry because of large-scale water abstraction [27]. Flow changes are likely to be exacerbated by global climate change owing to the increased frequency of floods and drought and, accordingly, an increase in water-engineering responses can be anticipated [28, 29]. Impacts on river biota are likely to be severe [3].

Physical pollutants to lakes and streams include materials such as particles of soil eroded from the landscape or washed from paved areas by flowing water [30]. Chemical substances deriving from human activities can cause problems increasing the concentration of pollutants [31]. Too much of one nutrient system can lead to excessive growth of plants, and synthetic organic compounds can cause physiological changes in aquatic organisms, or can become lethal at high concentrations. The pollutants can be taken by plants and animals through contact with contaminated sediment, or directly from the water [32]. Plants and organisms contaminated by these sources can pass the contamination through

Table 1. Groups mostly affected by threats to freshwater biodiversity. The intensity of impacts is represented by + or − (Source: [35]).

Threats to lotic biodiversity	Groups mostly affected	Intensity
Overexploitation	Plants, fishes, reptiles and some amphibians	++
Water pollution	Plants, fishes, amphibians, birds, mammals, invertebrates	+++
Flow modification	Fishes and invertebrates	++
Destruction or degradation of habitats	All groups of flora and fauna (microorganism also)	++++
Invasion by exotic species	Specialized species	+−
Hydropower	Fishes, mammals	+++

the food chain, as predators consume them. Stormwater, for instance, carries pollution from cities into rivers and lakes, yet most cities do not take sufficient measures to prevent runoff.

Bustos-Baez and Frid used the concept of indicator species using presence and/or absence of dominance of characteristic taxa to determine the degree of community change caused by the effects of pollution [33]. MacNeil et al. proposed that the ratio of two freshwater macroinvertebrate species (crustacean genera), Gammarus (Amphipoda):Asellus (Isopoda) may be useful as a crude measure of organic pollution for monitoring purposes over a period of time [34]. Fialkowski et al. [35] suggested the use of mayfly larvae as biomonitors of heavy metal pollution in streams since they can provide information on the different sources of bioavailable trace metals present in aquatic ecosystems. All these studies indicate the potential use of macrobenthic invertebrates as bioindicators of pollution [36].

At the same time, the loss of species can affect the water quality. Frequent studies on accelerating loss of species raise questions about why such losses are important, including the question of conserving biodiversity. Biologists in reply cite benefits to society that are often assumed to be offered by biodiversity; such as control of pests and diseases, the productivity of fisheries and the control of air and water pollution, among many others. Many of these supposed benefits have yet to be supported by rigorous scientific data. Recently, Cardinale [37] has produced a new study that verifies that biodiversity promotes water quality and explains how he does it. In particular, the study reveals how biodiversity helps remove excess levels of nutrients that commonly degrade water quality [37].

Vulnerability of freshwater biodiversity

The particular vulnerability of freshwater biodiversity also reflects the fact that fresh water is a resource that can be extracted, diverted, contained or contaminated so as to compromise its value as a habitat for organisms [38, 39]. In some cases, the impacts were sustained over the centuries and, in the case of many of the major rivers in China have persisted for more than 4000 years [8]. Some authors think it unlikely that a significant number of water bodies that have not been irreversibly altered by human activities will remain. The entity of most freshwater systems is not limited to their perimeter, but includes the basin from which the water and the material are drawn [40]. Their position in the landscape (almost always at the bottom of the valley) makes lakes and rivers ‘receivers’ of waste, sediments and pollutants in runoff [35]. This is true even for the seas and oceans, but water bodies, with a reduced volume if compared with that of the open marine waters, have limited ability to dilute pollutants or mitigate other impacts [3].

Moreover, in many parts of the world freshwater is subject to intense competition among multiple human actors, to the point that armed conflict can arise when water supplies are limiting and rivers cross political boundaries [41]. There are 263 international rivers, which drain 45% of the land surface of the Earth, and this area supports more than 40% of the global human population [42]. In the vast majority of agreements on the multiple uses of water, whether international or local, the allocation of water to maintain aquatic biodiversity is largely ignored [20]. In China and India, for instance, where there are about 55% of large dams in the world, almost no consideration was given to the allocation of water for downstream biodiversity [38, 43].

The combined influences and interactions of the major categories of threats have led to a decline in population and the reduction range of freshwater biodiversity in the world [35, 44].

The qualitative data suggest reductions in many freshwater vertebrates (for example a loss of 19 mammals, 92 birds, 72 reptiles and 44 species of fish). The population trends indicate a decline of an average of 54% among freshwater vertebrates with a trend towards higher values in tropical latitudes [45, 46]. In addition, 32% of amphibian species – dependent on wet and water ecosystems – in the world are now threatened by extinction. A much higher percentage of threatened birds (12%) or mammals (23%), and 168 species may already be extinct [17]. The well-known global decline of amphibians began during the 1950s and 1960s and continued at the current rate of about 2% a year, with more pronounced declines in tropical streams [47, 48]. This is close to the 2.4% estimated for the decline in freshwater vertebrate populations in the period 1970–1999 [49]. These estimates are extremely alarming [35]. The limited data on extinction rates in a few continent indicate a global freshwater 'biodiversity crisis' [50].

The rates of species loss from freshwater in temperate latitudes are not known with a degree of certainty. They are likely to be high because the species richness of many freshwater taxa (e.g. fish, macrophytes, decapod crustaceans) increases towards the tropics [51]. The drainage basins of many large tropical and subtropical rivers (such as the Ganges and Yangtze) are densely populated, with large dams that alter flow patterns and inevitable pollution from a variety of sources [8, 52]. For larger species in these rivers, the situation is precarious: the Yangtze dolphin (*Baiji*) is probably the most endangered mammal on Earth (now numbering fewer than 100 individuals; [8]) and the Gangetic dolphin (*Platanista gangetic*) is endangered according to the IUCN. The fauna of crocodiles in the Ganges and Yangtze is entirely endangered or highly endangered. Many other species of reptiles associated with water, and predominantly tropical, are seriously threatened [53], particularly turtles [54]. Many fish stocks are being overfished with risk of collapse of populations [8].

Alluvial ecosystems tend to be strongly influenced by the damming of the river channels and other modifications that alter and generally reduce the natural hydrological variability of the main rivers [35]. Major changes for purposes such as navigation and hydropower have been recently proposed for many of these river systems. These projects could affect large areas of flood plains through the alteration of the system of natural flooding [55]. Hydropower has significant potential in many developing countries to reduce greenhouse gas emissions replacing fossil fuels, but large-scale hydroelectric systems, in particular, can have adverse biodiversity and social effects [56].

Environmental and social impacts of hydropower projects are highly variable (table 2), depending on the pre-dam conditions, the maintenance of watercourses upstream and ecosystem integrity, design and management of the dam (e.g. the flow of the managed water), and the area, depth and length of the basin [35]. Small-scale river dams, generally, have fewer negative environmental and social effects. Anyway, sectoral environmental assessments can help in the design of systems with minimal negative consequences for ecological systems [52]. Moreover, well-designed installations, e.g. modern technologies that cascade water through a series of smaller dams and power plants, can reduce the negative environmental impacts of the system [52, 57].

Systems of small and micro-scale hydroelectric stations normally have low environmental impacts, but the cumulative effects of different projects within a stream can have a major impact on biodiversity in a wider area [35]. In general, the run-of-river projects have less impact than storage dams with large reservoirs, but can also have serious impacts on biodiversity [35]. These effects are mainly impeding the migration of fish by the physical barrier of the dam or through the drying of rivers below the dam (table 2).

Table 2. Environmental impacts of hydropower stations and operations (Source: [35]).

Impacts due to hydropower presence	Impacts due to hydropower operation
Upstream change from river valley to reservoir Flooding of terrestrial habitats Conversion of terrestrial habitats Changes in fish migration patterns Changes in vegetation	Changes in hydrology Changes in downstream and total flows Changes in seasonal and short term timing and fluctuation in flows Changes in high and low flows Local extinctions of fish species Changes in vegetation
Changes in downstream morphology of banks, delta, riverbeds, estuary and coastline due to altered sediment load	Changes in downstream morphology through altered flow patterns Reduction of connectivity
Changes in water quality, river temperature, nutrient load, turbidity, dissolved organic material, heavy metals and minerals	Changes in downstream water quality through altered flow patterns Changes in microorganism temporary communities
Loss of biological diversity Loss of animal migrations Changes in ecological succession	Decrease of riverine, riparian and floodplain habitat diversity Elimination of floods

Another important determinant of the impact of the dams is their location within the river system. Dams near the sources of the tributaries tend to have fewer adverse effects that can cause disruption across the entire basin [58]. The protection of the dams from siltation can be an incentive for mayor biodiversity conservation in the form of reforestation or afforestation measures within the basins [35]. The World Commission on Dams' guidelines for water and energy planning could be useful in this regard [59].

Global threats to freshwater biodiversity

Invasions and land-use change

Widespread invasion and the deliberate introduction of exotic species add threats to physical and chemical impacts of human beings in freshwater areas, partly because alien species are more likely to invade already modified or degraded freshwater [60, 61]. There are many examples of large-scale dramatic invasion effects on native species (e.g. Nile Perch in Lake Victoria, the crayfish plague in Europe, salmonids in the southern hemisphere lakes and streams [62]), and the impacts are expected to increase [20].

Indirect impacts may arise from terrestrial exotic plants such as *Tamarix* spp. (Tamaricaceae), which alter the water regime of the riparian soils and affect stream flows in Australia and North America [63]. Mountain mires are also threatened together with their unique biodiversity [64].

The urbanization of soils, as a transition from natural, semi-natural or agricultural use to an urban one, is a true 'consumption' of the soil, which produces an alteration of the landscape. The expansion of urban areas and related infrastructure are increasing the damage to freshwater biodiversity. Arienzo et al. show that the impact of land use and urban runoff on the contamination of the Sarno river basin in southern Italy has degraded the river water quality, especially near the river mouth [65].

According to Weijters et al. [66], a major threat to freshwater taxon diversity is the alteration of natural catchment land use for agriculture, industry or urban areas and the associated eutrophication of the water. In order to stop freshwater biodiversity loss, it is essential to quantify the relationships between freshwater diversity and catchment land use and water nutrient concentrations [66]. There are many untested hypotheses on the functioning of rivers in relation to land use and regime changes, and the consequential effects on aquatic organisms [60]. Aquatic science needs to move quickly into a manipulative or experimental phase, concerned with restoration and measuring ecosystem response.

Eutrophication and acidification

Eutrophication in lakes occurs naturally with the increase in the available nutrients [67]. Algae grow more when the water is enriched by anthropogenic pollutants. Eutrophication is one of the most serious problems for lakes worldwide [68]. The increase in water temperature has an effect on lakes similar to that of excess nutrients because the growth period in the lake ecosystem is longer [69]. This increases the availability of nutrients and decreases the predation of phytoplankton. The result is an uncontrolled growth of algae [70].

The more eutrophic a lake, the more sensitive it is to rising temperatures. With climate change and the melting of ice in recent decades, the deepest lakes remain longer stratified with warmer water near the surface and colder at depth. The lack of oxygen and the reduced exchanges in the deeper layers create ideal conditions for the proliferation of algae, with an increase of phosphates and nitrates being released from the sediments [71].

Acidification of water is mainly caused by atmospheric precipitation with nitrogen oxides (from motor vehicles) and sulphur oxides (mainly from the combustion of petroleum products and coal) [72]. These substances, when combined with water vapour in the atmosphere, produce acid rain, which alters the lake ecosystems. In a severely acidified lake, most animal and plant species die, but a few species such as mosses, green algae and some species of insects survive [73]. In many countries lakes, after maximum exposure to pollutant loads in the 1980s, are now suffering from the influence of moderate acids loads. For instance, a survey conducted from 1988 to 1991 showed that although the impact of acid rain did not cause serious damage to the lakes of Bolzano, in Italy, many high-altitude lakes have low values of alkalinity and are therefore sensitive to acids [74].

Emissions of sulphur compounds have greatly fallen since the early 1980s, but those of nitrogen oxides have not fallen to the same extent. Despite the current overall decrease in acid deposition, some acidification effects may occur in soil and water at high altitude in the most sensitive areas, where the rock is slow to release substances that can neutralize the acidity. An ‘acid shock’ can occur after the winter, when the chemical compounds accumulated in the snowpack are released all at once [75].

Climate change

The hot spots of global biodiversity contain exceptional concentrations of endemic species. Although habitat loss is increasing, most of the hot spots are geographically restricted and accordingly vulnerable to climatic changes (table 3), as there is a limited capacity for the movement of the species to less hostile conditions [35]. Any changes in rainfall and temperature will further impact freshwater ecosystems in these hot spots [76]. For example, the current and predicted water temperatures can exceed the thermal tolerances of aquatic fauna [77]. Consequently, the fauna cannot change their distribution towards the northern regions or in altitude as a response to increasing temperatures. Therefore, all mitigation

Table 3. Impacts of climate change on freshwater biodiversity and potential adaptation strategies (Source: [35]).

Impacts of climate change	Involved organisms	Potential adaptations	Extinction risk level
Water temperature increase	Fishes, plants, crustaceans, benthic species, turtles and mammals	Migrations northwards and upwards when not limited	Very high
Precipitation patterns changes	Fishes, vegetation, benthic invertebrates	Dispersal and *in situ* adaptations	Moderate
Water quality decline through higher temperature	Microorganisms, benthic invertebrates, plankton communities	Dispersal and *in situ* adaptations	High
Fragmentation of habitats, disruption or loss of migration corridors	Fishes, reptiles and mammals	Behavioural changes and phenotypic plasticity for generalist species	High
Invasion of species	Specialized species	Avoidance of competition (shifting of niches)	Low-moderate
Extreme events	All species (benthic species less affected)	Long distance dispersal	Moderate
Community composition changes	All species	New interactions and mutualism partnerships	High

responses must be *in situ* to produce a biophysical envelope suitable for improving the resilience of species [76, 78]. This could be done through an 'internal restoration' by increasing replantation in riparian zone at the basin scale.

According to IPCC [79], inland aquatic ecosystems are extremely vulnerable to climate change, particularly in Africa. Higher temperatures can cause water quality to deteriorate and will have negative impacts on benthic invertebrates and microorganisms. Plankton communities and their associated food-webs are likely to change in composition. It is likely that distributions of fish and other aquatic organisms will move north, but with some extinctions. Changes in hydrology and abiotic processes induced by changes in precipitation, as well as other anthropogenic pressures, will have large impacts on aquatic ecosystems. Boreal peatlands will be the most affected and undergo major changes in species composition. Many lakes are drying up; e.g. Urmia in Iran. The increase in the variability of precipitation regimes will also have a major impact and can cause loss of biodiversity in some wetlands. Seasonal migration patterns of wetland species will be interrupted [52]. The impact of an increase of CO_2 differs with the wetland types, but it can increase NPP in some systems and stimulate the production of methane in others [35]. Overall, ecosystem goods and services from aquatic systems are expected to deteriorate.

Climate change is expected to impact on lotic ecosystems in two main ways: first, through changes in the water cycle; secondly, through the associated changes in terrestrial ecosystems within a given basin (table 3). For inland wetlands, changes in rainfall patterns and floods in vast areas of arid terrain will adversely affect bird species that rely on a network of wetlands and lakes that are alternatively, or even episodically, moist and fresh, and more dry and saline [80].

These impacts can also be increased by habitat fragmentation or interruption or loss of migration corridors, or even changes in other biota, such as increased exposure to predatory birds [81].

The lack of thermal refuges and migration routes into streams and rivers can cause contraction of the distributions of many species of fish [35]. For example, higher water temperature in lakes reduces the concentration of dissolved oxygen and lowers the level of the thermocline, most likely with a consequent loss of habitat for cold water fish species. Besides, the reduction in summer flows and rising temperatures cause a loss of habitat suitable for cold water fish species in river ecosystems [60].

With regard to flows, the effects of changes in temperature-dependent areas would be, at least in the tropics, moderate in the middle latitudes and pronounced at higher latitudes, where the greatest variations in temperature are projected [35]. Rising temperatures alter thermal cycles of lakes and solubility of oxygen and other materials, and thus influence the structure and function of ecosystems [52]. The variations in frequency and intensity of rainfall, in combination with the change of land use in the watershed areas, have led to increased soil erosion and silting in rivers. This, along with increasing use of fertilizers, chemical fertilizers, pesticides, and herbicides as well as the deposition of atmospheric nitrogen, affects river chemistry and leads to eutrophication, with important implications for water quality, the composition of species, and fishing [35]. The extent and duration of the ice cover is projected to decrease in some high latitude lakes and, therefore, biodiversity can be affected by the short ice cover season [82]. Climate change will have more pronounced effects on wetlands through altering the hydrological regime as most of the inland wetlands processes are closely dependent on the hydrology of the river basins or coastal waters. This should affect biodiversity and phenology of wetlands species [83, 84]. As for terrestrial ecosystems, adaptation strategies to climate change in freshwater ecosystems include conservation and spatial interconnection [52].

Options for adaptation to these changes should take into account all the components of the basin [85]. River biota are naturally well suited to rapid and unpredictable changes in environmental conditions [86]. It may be essential to maintain or restore ecosystem connectivity, both longitudinally along the river and laterally between the river and its wetlands, in order to support the ecosystem function [87]. Many of the natural aquatic corridors are already blocked by dams and levees. This increases the vulnerability of biodiversity to climate change and constrains the implementation of adaptation strategies [35].

To adapt to climate change in inland waters, it is crucial to identify the degree of vulnerability of the various components of those complex ecosystems, and to base the subsequent development of appropriate ecosystem management plans on this information [88]. The management operations that favour natural hydrological function in the ecosystems close to inland waters are likely to benefit biodiversity conservation [35]. For many river systems, a change is inevitable. This recognition has stimulated much interest in the concept of supporting 'environmental flows' as a goal of river management [40]. These approaches must accept and adapt to the reality of climate change [60]. The increase in extreme weather events through climate change (for freshwater in particular the frequency and extent of drought and floods) is likely to be more a concern for isolated lakes and wetlands. The issue of extreme hydrological events, however, is of great importance to integrated planning and management of water resources. For example, the maintenance of flood plains of rivers and wetlands helps to restore the water balance and thus mitigate catastrophic floods [52].

Climate change, therefore, makes it urgent to manage inland waters better. There are considerable benefits both to conservation and national budgets from doing so. The natural form of preservation of the river and its ecosystem processes is likely to provide significant benefits for the coastal regions and populations. For example, freshwater ecosystems also play a significant role in the nutrition of nomadic reindeer-herders who take long pauses in rivers and lakes for fishing while maintaining their traditional way of life [35].

They have as much a right to a future as any urban person. Hunting is the oldest occupation of mankind, and many hunters of reindeer migrated across vast distances of Siberia throughout historical times [52].

The main impacts of climate change, which water management must meet, include increased flood risk, risk of drought, and change in flow regimes [60]. Common technical approaches to flood risk include the construction of levees and dams. Technical solutions are often applied to water scarcity issues, including the construction of reservoirs and channels, facilities for water diversion and abstraction from the rivers, and changes to river beds to improve the ability of transport during periods of low tide. Infrastructures can have significant environmental impacts, such as the destruction or alteration of wetlands, reduction of the connectivity between lakes, rivers and coastal areas, and the modification of sediment flows [52]. Restoration of mountain and floodplain areas is an environmentally sustainable alternative that deserves attention [35].

Climate change is leading to increased inland flooding in many regions under more variable rainfall. Restoring and maintaining ecosystems in river basins, including the management of soil and vegetation, can help reduce the risk of floods and continue the regular water supplies. Runoff from mountain areas in small islands is often the main water supply, and in many countries, watersheds are an essential part of the national economy [52]. Often these areas are degraded, and their rehabilitation is an adaptation option [60].

Wetland ecosystems in the basins reduce flooding and sediment deposition, and improve water quality downstream. A study of mountain forests in a watershed in Madagascar [89] estimated the value of protection against floods as US$126,700, and bog in Sri Lanka that buffer floodwaters of the rivers have an estimated annual value of over US$5 million [90]. In the Morogoro region of Tanzania, the reduced river flow and increased flooding have been attributed to deforestation in the mountains, and it was suggested that effective management of land, forests and water resources, and adaptation measures are necessary, along with improved social skills [91]. Ecuador and Argentina have integrated forest and wetlands management together with flood strategies, and reforestation is recognized as an important option for adaptation in the basins of the Philippines [60]. Vietnam includes measures such as integrated watershed management in its planning for disaster reduction, together with the management of forests and soil and water conservation. But Vietnam does not seem to be concerned about the impact of its control of the Mekong on other states. Afforestation projects on a large scale in China were made in order to reduce flooding and increase water conservation, and Central American countries are working together to protect the river and forest basins [92].

Climate change is causing an increase in the scale of floods and droughts in many floodplains. In some systems of dams adaptation strategies are no longer available, and in some cases dams have had negative environmental and socio-economic impacts. Even in these cases, the ecosystem management is a strategy of effective adaptation at the basin scale and an alternative to the development of small-scale dams [35, 93]. In developed countries, the reduction of cost-effective flood strategies, which allow the regrowth of vegetation along rivers and establish vegetation buffers along streams, combined with the reduction of infrastructure development, are promoted in some areas. Restoration of alluvial ecosystems can also help to reduce the levels of pollution of waters following extreme events [52].

There is new evidence of climate impacts on inland waters. Recent research has shown that there is a fourfold increase in the number of permanently dry ponds over the past 16 years and that this can be connected directly to the dramatic decline in populations and diversity of amphibians [94]. Modelling work suggests that climate change and other environmental changes may cause a change in the nature of river channels in Russian Arctic [95]. In the Arctic, factors such as the reduced ice cover duration on lakes, especially in the northern arctic areas, rapidly increases stratification rates and primary production, and decreases oxygen at depth. This will possibly result in a reduction in quality and quantity of habitat for species such as the lake trout. Reduction in summer flow of water is also likely to reduce the availability of habitat and possibly deny or shift accesses to the migration of fish [96, 97]. In monsoon-dependent Asia, interruptions in times and speeds of river flows will have great impact on the environment [48]. The interaction between climate change and changes in land cover is likely to lead to reduced discharge by many rivers, which in turn will lead to a significant loss of freshwater fish species [98].

There is also new evidence of the compositional changes in fish communities in France over the past 15–25 years [99], such as species richness, the warm-water species proportions, and the total abundance. There has been modelling of negative impacts on the habitats of endemic fish species, including freshwater salmon [75, 100], especially at higher elevations and in headwater areas [101]. In the Arctic, there is an expected decline of endemic fish such as Arctic and sub-Arctic species that migrate from the south to the north. The broad whitefish group (Arctic char) and Arctic cisco are particularly vulnerable to displacement.

Temperature is an important determinant of the distribution and survival of aquatic macroinvertebrates in high latitudes, and researchers have shown changes in species composition of boreal inland waters [102]. It has been suggested that the species characteristic of lentic systems can disperse more effectively than those of lotic systems [103], and therefore that the lentic systems can show more rapid change of composition in response to climate change [78].

The models show that climate change will also affect the composition of wetland species through its effects on river flow, especially at low water flows [75, 104], although the interaction with the socio-economic drivers of flow management is also very important. There is growing concern about the links between climate change impacts on aquatic systems, including warmer water temperatures, shorter duration of ice cover, altered runoff patterns, increased salinity, and increased demand for facilities (water conveyance and storage) and invasive aquatic species [105, 106]. Climate change is eliminating adverse winter conditions and will alter the distribution and ecological impacts of existing alien species, enhancing their effects on competition and predators on endemic species, and increasing the virulence of some diseases [81, 107]. The forecasts for Canada indicate that the water temperature can change as much as 18 °C by 2100, which means that a number of lakes will just be vulnerable to invasion from perch [108].

Other factors that interact with climate change in determining the change in the composition in inland waters include eutrophication [78], acidification [109, 110], and land cover changes [78], with alterations in the composition of the Earth's systems, and agricultural expansion [78, 111]. There is very little information on the actual or anticipated changes in aquatic ecosystems in the tropics, but it is clear that some important tropical wetlands are threatened by altered freshwater flows [75, 112]).

Some other significant impacts of climate change are expected both for carbon storage and fishery services of inland waters. Although this forecast is especially strong for the Arctic [74], there is also a growing body of model-based figures for other regions [75]. A new concern is the effect of the increase of carbon storage above sea level in coastal wetlands, including the worldwide 150,000 km^2 of freshwater bogs 5 m below sea level and vulnerable to rising level of sea. They are likely to emit significant amounts of carbon when they are inundated [113]. Conservation of biodiversity in coastal wetlands is also at risk (e.g. the Sundarbans, the world's largest wetland, is threatened by altered freshwater flows and the rise in sea level, both of which are affected by climate change) [86]. The ecosystem services provided by peatlands are also at risk, as expected temperature changes will reduce their function as carbon reservoirs [114].

Global scenarios for freshwater biodiversity

Recent trends suggest that a combination of climate change, water withdrawal, pollution, invasive species, and the construction of dams further worsen the current status of freshwater biodiversity [115]. The particular vulnerability of freshwater species to global changes reflects the fact that both freshwater biotic and abiotic resources have been overexploited for a long time. Scenarios for biodiversity of freshwater are fewer than those for terrestrial and marine biodiversity [116]. In addition, global scenarios tend to focus on water resources for people, but rarely include freshwater biodiversity. The exceptions model a limited number of drivers and treat only qualitatively an important driver, such as the construction of dams, eutrophication, and invasive species [35]. Habitat loss and fragmentation are among the greatest threats to biodiversity in the world, and this is certainly important for river fish [3]. It is almost certain that disturbance of freshwater ecosystems as by dams, reservoirs and diversions for irrigation and industry, will put in danger or extinguish many species of freshwater fish, by creating barriers to normal species movements and migration and decreasing the availability of habitats [35].

It is difficult to make accurate predictions about how climate change will affect the biodiversity of fish, even though the climate niche modelling suggests that, at the local level, the number of warm-water species may increase in the temperate zones and some cryophilic (cold water) species may disappear regionally [89]. Narrow endemic river fish can be particularly threatened by climate change. The biggest problems occur in basins that have an east-west configuration, while in basins with a north-south configuration, there will be more opportunities for migration and adaptation, until the rivers are not blocked by dams [89]. The models project also that in shallow lakes in northern latitudes summer fish species of cold water could disappear because of both the high temperatures of the water and decreasing dissolved oxygen.

Other negative effects of climate change on freshwater ecosystems are changes in snow melt timing and volume flow. Global climate scenarios were applied to the known relationships between the diversity of fish and river discharge. Results predict decline in freshwater biodiversity in approximately 15% of the rivers around the world in 2100, a combination of runoff reduction (caused by climate change) and increased water withdrawals for human use [89]. These forecasts should be treated with considerable caution, as the approach does not provide the true extinction rates, but instead a percentage of species 'committed to extinction' with a specified delay time. These forecasts do not include other current stresses in the area of freshwater fish, such as river pollution or fragmentation [117].

Based on the established relationship between the number of non-native fish species and human activities, the river basins of the developing countries should be able to accommodate a growing number of non-native fish species as a direct result of economic development [118].

Dams and climate change can facilitate the expansion of invasive species and diseases associated with lacustrine ecosystems [119]. Pressure on freshwater ecosystem services

[120] and degradation of wetlands will increase and this will lead to deterioration of services regulating water quality and flood protection. The combination of population growth and climate change will cause increased numbers living in river basins to face severe water stress [121, 122]. This will not only increase the risk of chronic water shortages, but also cause serious negative impacts on freshwater ecosystems [89].

Many studies report that eutrophication of freshwater systems will increase in the world's developing countries as the use of fertilizers and untreated sewage effluent continue to increase [123]. This may be further aggravated in some regions by decreasing precipitation and increasing water stress. The transition to eutrophic conditions is, in some cases, difficult to reverse and can lead to the loss of fish species, the loss of recreational value, and in some cases health risks for human populations and domesticated animals [124–126].

Conclusions

Freshwater ecosystems support thousands of species, although their conservation and management are critical, and biodiversity of fresh water is a precious natural resource. These ecosystems are experiencing biodiversity declines greater than those of the most affected terrestrial ecosystems, and the likelihood of conserving much of the remaining biodiversity in fresh water appears to be very low.

These ecosystems are threatened by many anthropogenic stresses such as overfishing, water pollution, flow changes, destruction or degradation of habitat, invasion of exotic species, hydroelectric power stations, and climate change. For example, the cumulative impacts of small dams on biodiversity need to be considered, even when individual installations may have only minor ones.

Climate change is already affecting the ability of ecosystems to regulate water flows. Regulation of quality and quantity of water is a key ecosystem services worldwide. Higher temperatures, changing radiation and cloud cover, and the degradation of ecosystem structure result in the appearance of new and higher flow peaks, and also hinder the ability of ecosystems to adjust the flow of water. This has important consequences both for ecosystems, with associated species assemblages, and people, in the scale of whole catchment areas. In addition to many types of forests and wetlands in freshwater, fluvial and alluvial ecosystems, are affected by changes in the hydrological regime. The loss of wetlands because of over-extraction of groundwater, drainage for human use, reduced runoff, and the rise in sea level, reduces biodiversity and negatively impacts the services of regulation of wetlands, such as water purification and mitigation.

Finally, biodiversity can play a role in adaptation strategies for both droughts and floods through the management of river basins, wetlands, forest and agricultural systems. Maintenance or restoration of forests and wetlands can reduce runoff in times of floods and also increase water retention during droughts. Planting trees on sloping fields, mini-terraces for the conservation of soil and moisture, and improved grassland management can also integrate conservation as much as can the construction of small-scale infrastructure in water management.

Disclosure statement

No potential conflict of interest was reported by the author.

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