Threats to Freshwater Biodiversity in a Changing World

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Contents

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Definition

Fresh waters cover <1 % of the Earth's surface, yet host around 10 % of known animal species. This biodiversity is threatened by a combination of factors, exacerbated by the position of rivers and lakes as landscape "receivers." Climate change will intensify competition for water with humans, causing further declines in freshwater biodiversity.

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Freshwater Ecosystems: Scarcity, Richness, and Vulnerability

Much of the Earth's surface is covered with water, but only a small fraction – around 2.5 % – is fresh (i.e., its salt content is less than 1 part per thousand). However, around two-thirds of the fresh water is frozen solid at the poles (especially Antarctica), and the other third is deep underground. Thus only a tiny portion (0.3 %) of fresh water remains on the surface in liquid form; it is all that is available for aquatic organisms to live in. To put it another way, freshwater ecosystems (sometimes termed inland waters), constituting no more than 0.01 % of total global water resources, occupy less than 1 % of the Earth's surface area. Most of this water resides in lakes, and fully 22 % of it occurs in Lake Baikal, Siberia. Rivers contain a mere 0.006 % of surface fresh water (or 0.0002 % of all water) equivalent, at any moment in time, to a volume of around 2,120 km^3. The tiny fraction in rivers is the source of most water used by humans and serves as habitat for many organisms found nowhere else.

The global **scarcity** of fresh water has profound implications for nature and for humans. With respect to the former, the habitable area (or volume) – literally, the living space – for freshwater organisms is small. One might therefore expect that freshwater ecosystems would support few types of plants and animals, but, on the contrary, freshwater biodiversity (=biological variety: used herein to refer mainly to numbers of animal species) is remarkably high. A few statistics make this clear (Dudgeon et al. 2006; Balian et al. 2008; Strayer and Dudgeon 2010). Approximately 125,000 freshwater species have been described and named by scientists; they represent 9.5 % of known animal species on Earth, including around one-third (>18,000 species) of all vertebrates. Most of these (one quarter of all vertebrates) are fishes, and the rest comprise the entire global complement of crocodilians, virtually all of the amphibians, and most of the turtles. Considering just the bony (actinopterygian) fishes, species richness in the oceans and freshwater is similar (~15,000 species each, with none in common) despite the greater productivity of marine environments. This remarkable **richness** is also disproportionate to the area occupied by freshwaters.

The scarcity of fresh water has obvious and important implications for humans. A significant proportion of the global population (~0.9 billion people) lacks ready access to drinking water, and perhaps 40 % (>2.5 billion) of people do not have adequate sanitation; child deaths resulting from contaminated water may be as high as 1.5 million annually – as many as 5,000 *each day* (WHO/UNICEF 2008). The demand for water has increased fourfold during the last 50 years, and the global population, which recently topped seven billion, is projected to reach nine billion by 2050 or thereabouts. Water for irrigation will be essential to feed these two billion additional people and improve the nutritional status of many others currently undernourished. Humans already appropriate 54 % of surface runoff and, although estimates of this proportion vary somewhat, increases in the foreseeable future could transgress planetary boundaries for sustainable water use (Rockström et al. 2009). While water-saving and irrigation technologies may slow the rate at which demand grows, the scope for further appropriation of water is limited as many rivers and lakes are situated in parts of the world (such as the far northern latitudes) where the inhospitable climate limits agricultural potential.

The key point is that almost 10 % of global animal biodiversity is associated with fresh water covering less than 1 % of the Earth's surface. This fact stands in stark juxtaposition to ever-growing human demand that results in consumption and contamination of the water which sustains that diversity. The **vulnerability** of freshwater to anthropogenic impacts is increased by the tendency for such impacts to be felt some distance away: for instance, changed land use within a drainage basin alters the timing, quantity, and composition of runoff, and the topographical position of rivers and lakes ensures that they are the eventual recipients of any and all material originating within their drainage basins. Furthermore, the unidirectional flow of rivers, together with the hierarchical arrangement of tributaries, means that impacts are not confined to one locality but transmitted downstream. Thus rivers are "receivers" and "transmitters" of contaminants and other materials, whereas lakes are "receivers" and may serve as sinks or "accumulators." All freshwater are also "integrators" of the combined impacts of human activities within their drainages.

To make matters worse, fresh waters are insular habitats – i.e., they are islands within a terrestrial matrix – and river drainages are isolated from each other by mountains or coastal waters that cannot be traversed by most freshwater animals. These barriers to dispersal limit the exchange of individuals or their genes, and the resulting isolation produces a considerable degree of local endemism: i.e., species become adapted to particular conditions within a lake or river, each of them having small geographic ranges relative to their terrestrial or marine counterparts. The outcome of insularity and endemism is high species turnover among lakes and river basins, accounting for the high richness (in per unit area terms) of freshwater animals. This turnover increases the vulnerability of freshwater animals to human impacts, because rivers and lakes (especially ancient lakes) tend to contain unique combinations of species that are not "substitutable," and each drainage makes an irreplaceable contribution to the regional species total. Thus species loss from a single river or lake could represent global extinction.

In combination, the scarcity of fresh water ensures that there is competition for water between humans and nature, while the insular nature and disproportionate *richness* of freshwater has the consequence that their degradation can lead to significant biodiversity losses. These losses are made more likely by the unique *vulnerability* of freshwater ecosystems since they serve as receivers, integrators, and sometimes transmitters of human impacts within their drainage basins. These three features collide within the "perfect storm" of human population growth and increasing water needs: as human requirements for water go up, that which remains for nature declines; the opposite does not apply.

What Are the Threat Factors?

The "perfect storm" is constituted by a number of separate but interacting elements:

- *Pollution* of all types caused by inorganic or organic substances from point (e.g., end of pipe) or diffuse (overland runoff or seepage) sources, often comprising complex mixtures, with direct consequences ranging from lethal through acute to chronic (crossref. needed). Impacts can be indirect if pollutants reduce habitat suitability; for instance, soil runoff clogs riverbed sediments used by spawning fish.
- *Flow regulation* used generally to encompass water abstraction for irrigation and other purposes; construction of large and small dams for water storage, flood control, or hydropower generation; long-distance transfers of water between drainages; and river channelization or canalization with associated dykes or levees that separate rivers from their flood plains. In extreme cases, a complex river corridor can be transformed into a massive, concreted drainage ditch. Dams and weirs are barriers to the movement of organisms and material within river networks, presenting a critical constraint for migratory fishes. Dams also degrade rivers by transforming the section upstream into an impoundment of standing water, while the flow downstream depends upon dam operations and may not resemble the original regime; sediment loads, oxygen content, and temperature of released water are likewise altered. Natural flow or inundation patterns – to which animals are adapted and upon which they depend – are modified, seasonal patterns of flow variability or water level fluctuations are reduced, and river dewatering or lake bed drying may even occur.
- *Overexploitation* impacts animals used for food, mainly fishes but also frogs, some reptiles, and a few crustaceans and molluscs. Overfishing typically results from high catch effort, with larger, more long-lived species (often predators) tending to decline first, whereupon the fishery shifts to smaller, fecund species with short life cycles. Migratory species are particularly vulnerable, since they are often caught during movements that take place prior to breeding, so diminishing the capacity for stock replenishment. Declines also result from use of damaging fishing gear (fine-mesh nets, electrical devices, explosives, or poisons) often adopted as methods of last resort after larger fishes have been depleted. Crocodiles and turtles have been hunted, close to extinction in some cases, for their hides or other body parts, and unionid or "pearly" mussels in the United States were exploited for their pearls and nacreous shells (used to manufacture buttons) during the late nineteenth and early twentieth century; some species have yet to recover.
- *Drainage-basin alteration* such as vegetation clearance affects the water balance within drainage basins and usually increases erosion. Changes in runoff quantity are accompanied by reduced quality (contaminants from farmland, towns, and cities) so degrading aquatic receivers. Clearance of riparian zones (along lake shores or river banks) and floodplains impacts semiaquatic animals (otters, herons, etc.) that live along water margins and amphibiotic species (frogs, dragonflies, etc.) that spend their adult phase on land.

- *Invasive species* are nonnative to a particular region but have been introduced (accidentally or deliberately) by humans and become established. They are also known as introduced, exotic, or alien species, but the use of the term "invasive" denotes nonnative species that established themselves and spread at the expense of native species. Typically, invasives are effective competitors or efficient predators or possess an attribute lacking among members of the receiving community, but others cause damage by introducing parasites or diseases (including fungal chytridiomycosis that affects frogs). There is scant taxonomic constraint upon what makes a successful invasive. The category encompasses aquatic plants, snails, mussels, crayfish, mosquitoes, turtles, frogs, a few waterfowl, and many fishes (see the Global Invasive Species Database). The establishment of large, predatory Nile perch (*Lates niloticus*) – categorized among the 100 "World's Worst" invaders – in Lake Victoria, East Africa, and the consequential disappearance of >200 species of endemic cichlid fishes, is but one example of the potential for damage.
- *Interactive effects* among these five threat factors, and their multifarious components (including many not listed above), are pervasive since they can act simultaneously upon the same habitat. Indeed, the extent of drainage-basin alteration and pollution are often correlated. Habitat alteration may make animals more vulnerable to pollutants or, conversely, sublethal effects of contaminants may compromise their ability to adjust to changed conditions. New conditions may, in turn, facilitate establishment of invasives, and the greater the extent of habitat alteration, the less likely are native species to persist. In addition, pollution and habitat alteration limit the ability of fishes to withstand or recover from exploitation, and dams may prevent them for accessing breeding sites up- or downstream. In short, the five threat factors can combine to produce synergistic outcomes that can be difficult to predict and exceed the sum of their individual impacts.

What Are the Global Patterns of Threat?

A recent global study of river health (Vörösmarty et al. 2010) addressed the relative intensity of anthropogenic threats to both human water security and biodiversity. The two analyses each combined 23 weighted threat factors or stressors (termed "drivers") within four categories: drainage-basin alteration, pollutants, water-resource development (i.e., dams and flow regulation), and biotic threats such as overfishing. However, the weighting applied to each driver varied between the two analyses, since their impacts differ greatly depending on whether they are felt by humans or (say) river fishes. For example, building a dam could be beneficial for human water security, whereas the effects on river fishes are negative. Conversely, mercury tends to accumulate along food chains posing a danger to apex consumers (crossref.); it is thus a greater threat to humans than to most fresh water organisms. Despite these separate driver weightings, low levels of water human security and high endangerment of biodiversity were generally correlated (Vörösmarty et al. 2010). But, as Fig. 30.1 shows, the match between the two is not complete: there are places, mainly in Europe, North America, and Australia, where incident threats to human water security have been ameliorated by considerable investments in hard-path engineering and water treatment. There has been no comparable outlay to protect biodiversity, and thus conditions in such places are "good" for humans but "bad" for biodiversity. Elsewhere, and especially in densely populated parts of the developing world, the spatial pattern of threats to human water security and biodiversity is remarkably congruent: conditions are "bad" for humans and biodiversity (Fig. 30.1). Most notably, there seem to be no places where human water security is at risk in the absence of any threats to freshwater biodiversity, illustrating the tendency for human water requirements to take precedence over the needs of nature.

What Is Threatened? What Has Been Lost?

While we cannot, yet, map the responses of freshwater biodiversity to variety of global-scale threats outlined above, we can nonetheless be confident about the extent and severity of changes that have already taken place (e.g., Dudgeon et al. 2006; Strayer and Dudgeon 2010). Given that human activities are already causing losses of marine and terrestrial species at least one to two orders of magnitude in excess of background extinction rates derived from the fossil record (Rockström et al. 2009), we must also have far exceeded whatever margins would have been sustainable for freshwater biodiversity. Population trend data consolidated in the Living Planet Index (WWF 2010) confirm this with steeper declines in animals living in fresh water than those on land or in the sea. Anadromous species, such as American shad (*Alosa sapidissima*) and Atlantic salmon (*Salmo salar*), that migrate between the sea and freshwater to breed have been especially hard hit, with declines in abundance of up to 95 % in rivers draining into the western Atlantic (Limburg and Waldman 2009). The IUCN Red List likewise reveals that a host of freshwater species is extinct or imperiled. For example, 38 % of freshwater fishes in Europe and 39 % in North America meet IUCN criteria for endangered-species status, incidentally underscoring the fact that securing human water needs by investments in river engineering and water treatment does nothing to relieve threats to freshwater biodiversity. Overexploitation and international trade of freshwater turtles due to their use in traditional Chinese medicine is reflected in the large number of species categorized as globally endangered. Inadequate knowledge of tropical freshwater biodiversity (Balian et al. 2008) adds some uncertainty over how much is being lost: while 31 % of 6,374 (mostly tropical) amphibian species are categorized as threatened by the IUCN, another 25 % of them are classified as data deficient (DD) because data on population trends are insufficient for a reliable conservation assessment. This pattern is more marked for Asian freshwater turtles: virtually all the non-endangered species are DD because they are rare, implying that they are already endangered. Data for most invertebrate taxa, as well as algae and microbes, are insufficient to determine global patterns of endangerment, but for some

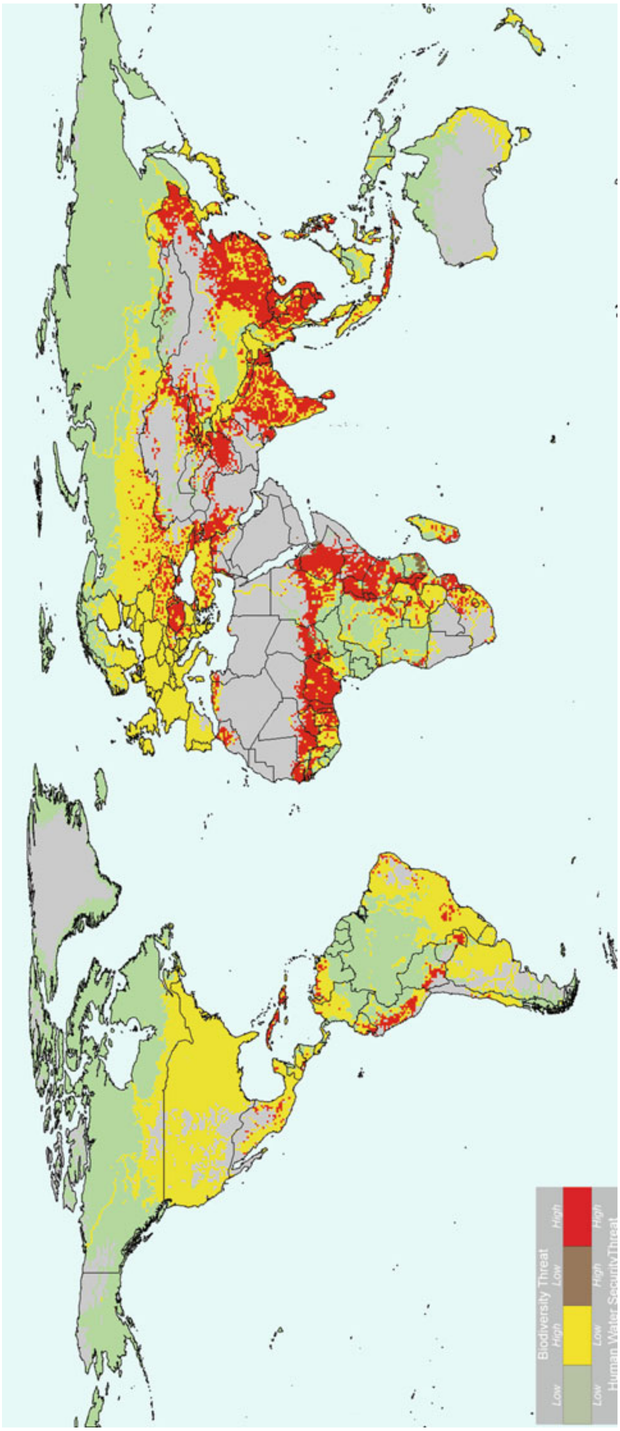

Fig. 30.1 A global geography of river threat, showing the patterns of spatial concordance of aggregate threat from 23 drivers (see text) to human water security and freshwater biodiversity. Areas shaded *gray* have no appreciable river flow. Image from www.riverthreat.net

groups (e.g., freshwater bivalves: 38 % classified as threatened by the IUCN) there are grounds for concern about species loss.

Declines in freshwater species, including the first human-induced extinction of any species of cetacean (the Yangtze river dolphin, *Lipotes vexillifer*), are a reliable indicator of unsustainable use of freshwater by humans with consequences that have outpaced attempts at management (Dudgeon et al. 2006; Strayer and Dudgeon 2010). To this can be added a substantial extinction debt due to human actions that have reduced populations to levels from which they can no longer recover, as well as losses that occurred in the past that have been overlooked or forgotten. One example is the gradual disappearance, since medieval times, of beaver (*Castor canadensis*) from much of its former range in Europe. Another is American shad which supported a major commercial fishery along the western coast of the United States during the nineteenth century that has long since collapsed. Imperfect knowledge of past conditions in freshwater gives rise to "shifting baseline syndrome" whereby we are deceived by the false impression that conditions in the immediate past reflect conditions in the intermediate and distant past, so that we underestimate the extent of human impacts (Humphries and Winemiller 2009). The shifting baseline reduces expectations of what species should be present in freshwater, even in the case of economically important species, such as shad, soon after dams or other insults have eliminated them from particular rivers (Limburg and Waldman 2009).

What of Climate Change and the Future?

Climate change was not included in the list of threat factors given above nor is it taken into account in the global river threat analysis shown in Fig. 30.1. Impacts on freshwater will arise from rising temperatures and alterations in rainfall and increased frequency of extreme climatic events, as well as medium-term effects such as glacial melt. There is already evidence of warmer water temperatures, shorter periods of ice cover, and shifts in the geographic ranges and seasonality of freshwater animals in northern latitudes (reviewed by Heino et al. 2009). Climate change does not augur well for freshwater biodiversity in regions where the human footprint is pervasive, since this is where conflicts over water will be most intense and the outlook for biodiversity correspondingly bleak. Warmer temperatures will mean greater water use by plants (crops, pasture, and natural vegetation), correspondingly less runoff or percolation to sustain rivers and lakes, and more water abstraction for irrigation. Changes in temperature and/or flow and inundation patterns could cause shifts in the timing of breeding or migration by fishes, and even the disappearance of seasonal cues for such life-cycle events. Consequences for reptiles, such as turtles and crocodiles in which the sex ratio is determined by temperature, could be extremely serious. Ultimately, conditions in rivers and lakes may no longer be suitable for species that evolved there, and there will be limited opportunities for overland dispersal by aquatic animals to more suitable habitat.

An additional source of threat to freshwater biodiversity will originate from human adaptation to a more uncertain climate (increased floods and droughts), which is likely to stimulate dam construction for water storage, flood control and hydropower, and engineering work to mitigate potential water shortages or threats to human life and property arising from a more uncertain climate. These responses will magnify the direct impacts of climate change on biodiversity because they degrade freshwater ecosystems and limit their natural resilience. Furthermore, increased abstraction of water from lakes and rivers, combined with warmer temperatures, may increase the concentrations and toxicity of pollutants, interacting with existing uncertainty about the combined impacts of contaminant "cocktails" (crossref.). Climate change may also facilitate invasive species that threaten native biodiversity, through direct alterations in habitat conditions (warmer temperatures) or indirectly via construction of dams and impoundments where invasives can become established and spread to other locations.

What Now?

With a few notable exceptions, freshwater biodiversity has – until recently – been largely overlooked by conservation scientists and the public, receiving only a fraction of the attention devoted to terrestrial or marine species. The result has been continued overexploitation of fish stocks and construction of dams that have altered habitats and access to breeding sites. Potential effects of pollution have received more attention, because of the direct implications for human health and water security, but drainage-basin alteration continues to be prevalent and rapid, while insufficient efforts are being made to address spread or impacts of invasive species. Thus, a first priority must be raising awareness of global declines in freshwater species and combining this with explanations of the value of this biodiversity to humans; demonstrations of the importance of well-managed inland fisheries would be a good place to start. Attention needs to be paid to restoring or rehabilitating habits and species in parts of the world where human water needs are relatively secure, but biodiversity remains under threat (Fig. 30.1), and action plans for management of critically endangered species need to be drawn up as a matter of urgency. The need to address water and sanitation needs of humans must take explicit account of concerns over biodiversity. Where trade-offs must be made, societal decisions should be taken with full knowledge that securing water for humans may be detrimental to biodiversity, rather than the prevailing approach where little or no account is taken of freshwater biodiversity and supporting ecosystems. There may be opportunities to meet human needs for clean water without resort to the plethora of hard-path engineering measures adopted widely in Europe and North America, thereby reducing impacts on biodiversity. Environmental water allocations for freshwater ecosystems (Poff et al. 2010), including controlled release of water from dams, is another measure that could be implemented. Finally, we need to facilitate the persistence of freshwater biodiversity in the context of a changing climate.

If "stationarity is dead" (because climate change is altering means and extremes of temperature, rainfall, and river flow), then we must accept that conditions in lakes and rivers will alter more quickly than their inhabitants will be able to adapt to them. Given that dispersal opportunities to new habitats are constrained for most freshwater animals, can and should we consider their assisted translocation to potentially suitable sites (Olden et al. 2011) where their long-term persistence would be more likely? There is an urgent need to address all of these issues, if we are to avoid becoming overseers of more dramatic declines and extinctions of freshwater species than witnessed thus far.

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Additional Recommended Reading

Global Invasive Species Database. http://www.issg.org/database/welcome/

IUCN Red List. www.iucnredlist.org

Rivers in Crisis. Mapping dual threats to water security for biodiversity and humans. www.riverthreat.net

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