River Conservation
Challenges and Opportunities

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Chapter 6 Offprint

Anthropocene Extinctions: Global Threats to Riverine Biodiversity and the Tragedy of the Freshwater Commons

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Chapter 6

Anthropocene Extinctions: Global Threats to Riverine Biodiversity and the Tragedy of the Freshwater Commons

David Dudgeon

Fresh water is a scarce resource, variously over-used and contaminated, subject to conflicts among humans whose needs are met at the expense of water required to sustain ecosystems. This tragedy of the commons defines the Anthropocene as an epoch marked by river degradation and unparalleled global endangerment of freshwater biodiversity.

6.1. The tragedy of the commons

The story is a familiar one, and has origins in the writings of ecologist Garrett Hardin over 40 years ago. It goes something like this. A villager puts a goat out to graze on the common land around his settlement, so that his family can have a regular supply of milk. Seeing their neighbour enjoying this benefit, each of the other villagers sets their own goat to graze. The village is small, and all goes well until one villager realizes that he can gain more milk by putting out two goats. He does so, and soon his observant neighbours do the same. The numbers of goats increase to the extent that there is less grass for each of them to eat, and thus their per-capita yield of milk is lower than when each villager kept only one goat. The combined yield of the two goats is nonetheless greater than that from a single goat, so the villagers are better off. Soon, one of the villagers is tempted to put a third goat on the commons; his neighbours follow suit. A fourth goat is added… and so on. The additional increment of milk from each goat decreases as the goat population increases, but so long as the villagers obtain some benefit from adding another animal, the number of goats on the commons increases. The additions continue until the grass on the commons can no longer withstand the intensity of livestock grazing. It dies back, the goats starve, and the supply of milk to the villagers dries up. The lesson here is that protection of the environmental commons requires individuals to forego some gain: rather than maximizing the amount of milk they can obtain in the short term, it is wiser to limit the number of goats and optimize the long-term gain of milk by ensuring the commons is not overgrazed and thereby managed in a sustainable fashion.

Why is the tragedy of the commons relevant to fresh water and rivers? Water is an irreplaceable resource for humans and biodiversity, and consumption or contamination of water by one group of human users renders it unavailable or unfit for other users. Furthermore, water is used in a number of ways that are often incompatible: for instance, the extraction of river water by farmers for irrigation makes it unavailable to sustain fish stocks and impacts those who make a living from fishing. Other uses of the same water if it remained in the river channel might include generating hydropower, flushing wastes downstream, allowing navigation, or sustaining biodiversity. Because such uses for humans and non-humans often conflict, fresh water is the common resource *par excellence*. Moreover, equitable use of shared water requires human users to forego gains: the farmer must limit the water he extracts for irrigation so that users downstream can enjoy some benefit; likewise, the industrialist must treat effluent – thereby limiting profits – rather than simply discharging untreated waste water. The tragedy of the freshwater commons is that individual users rarely forego gains voluntarily, yet the rest of the community of users must share the negative consequences of those gains. In short, it is in the interest of individual water users to over-extract or to contaminate because they profit more from doing so than from not doing so; polluters also benefit from the convenient fact that river water flows downhill so their impacts are felt elsewhere.

The potential for conflict among user groups is evident from consideration of the benefits arising from construction of a hydropower dam on a river. People dwelling downstream of the dam, or in cities some distance away, receive the benefits of flood control and electricity. More locally, farmland may be inundated by the reservoir formed behind the dam, and the livelihoods of fishers are compromised by changes to river ecology. In this example, the impacts of the dam are felt locally, typically by the rural poor, whereas the benefits accrue some distance from the site of the dam. All too often, decisions about dam construction are made by city-dwellers who have more political influence than people who are directly affected by the dam and receive no benefit from it. To put it another way, the freedom (or "rights") of parties who stand to gain economically from generating electricity conflicts with the freedom (or "rights") of others to derive livelihoods from the intact river. In any case, scant consideration is given to the need to conserve aquatic biodiversity or preserve ecosystems when conflicting human interests are at stake. An outstanding example of this potential for conflict, and the resulting damage to biodiversity of river fishes, their fishery and human livelihoods along the Mekong River, is shown in Box 6.1. This case has yet to play out fully, and so the possible extent of its implications remains unclear.

Box 6.1

Conflict over the freshwater commons: The case of the Mekong River

The Mekong is an international river that flows through China into the Lao People's Democratic Republic (PDR) and Thailand (where it constitutes part of the boundary between these two countries) thence into Cambodia and Vietnam (Figure 6.1). Its biodiversity has yet to be fully inventoried, but may include as many as 1300 fish species, placing it among the top three rivers in the world in terms of fish richness (Dudgeon 2011). The portion of the river downstream of China, referred to as the Lower Mekong Basin (LMB), supports the world's most productive freshwater fishery, with annual catches (fishes plus shrimps and frogs) amounting to around 2.5 million t worth almost US$4 billion at first sale and perhaps close to twice that as processed products. To put this in context, it represents one quarter of the estimated global freshwater catch. Much of this bounty is based upon a suite of around 50 species of migratory fishes. The importance of this multispecies fishery is evident from the fact that fishing is at least a part-time activity of 40 million inhabitants of the LMB, and the protein obtained from this source is of great dietary significance, especially in Cambodia and land-locked Lao PDR.

The migratory patterns of Mekong fishes are complicated, and different parts of the LMB may support different migratory species that follow a variety of routes at slightly different times. These combine with variations in the topography of the land and extent of the floodplain to result in differing fishery yields across the LMB, with catches being greatest in the lowest section of the river where the floodplain is most extensive (Figure 6.1). As a generalization, migrations of the majority of species are linked to the annual flood cycle, with upstream or lateral movements of fishes initiated by increased flows and floodplain inundation at the start of the monsoon season in May. Migrations are accompanied by breeding, and return movements of adult fishes from upstream or the floodplain – as well as the arrival of young-of-the year – takes place when water levels fall as the monsoon wanes during September or October. Thus seasonally-fluctuating flows, return migrations and floodplain inundation are all essential features of the productive LMB fishery, and the yield from the river depends

Box 6.1 *(cont.)***: Conflict over the freshwater commons: The case of the Mekong River**

on sustaining the natural flow pattern and unimpeded movement of fishes.

Conflicts over how best to manage this all-important fishery have been thrown into stark relief by plans of the Lao PDR to build a hydropower dam on the Mekong mainstream (Dudgeon, 2011). The 49 m high Xayaburi dam (Figure 6.1) will have a 100 km long reservoir with a dramatically different flow regime from the river mainstream. It will be a barrier to up- and down-stream migrations of fishes (and downstream transport of drifting larvae), and trap sediments and associated nutrients that would otherwise be transported to downstream portions of the LMB. Since the dam will be situated in the less-productive upper migration zone (Figure 6.1), overall LMB fish yields may be reduced by less than 10% but, within Lao PDR, the reduction in the floodplain fishery could be 70%. Offset against this loss would be the economic gains from the generation and sale of electricity (mostly to neighbouring Thailand), but it seems remarkably short-sighted of the Lao PDR government to trade this off against devastation of a natural larder that provides a significant portion of the nation's animal protein needs. This is indicative of conflict of interests among those making policies and many rural inhabitants likely to be affected by them. The downstream riparian states, particularly Cambodia, are deeply concerned about the possible impacts of the Xayaburi dam on LMB fisheries, and have voiced concerns at the Mekong River Commission (MRC), an inter-governmental organization established

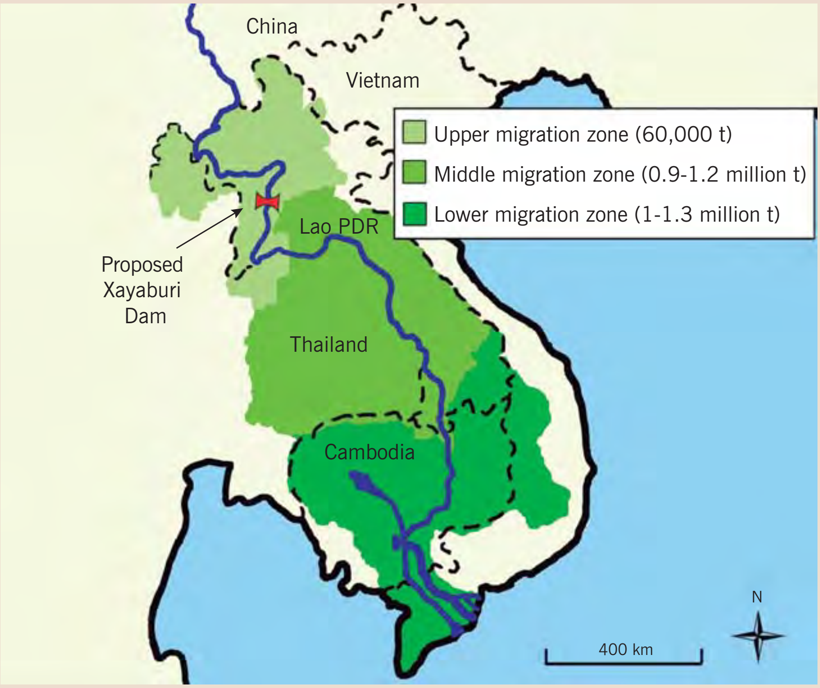

Figure 6.1: *The Lower Mekong Basin showing the annual catches from the three main fish migration zones. The location of the planned Xayaburi Dam within the upper migration zone is also shown*

in 1995 by the four LMB riparian states with the aim of facilitating sustainable development, management and conservation of the river. Despite the need for Lao PDR to obtain the agreement of the other MRC member states to any plan to build a mainstream dam, at the time of writing no consensus has been reached and site preparation has begun. Resolution of this international conflict may be problematic as the MRC has no mandate to interfere with the decisions made at the national level by any of its members. Moreover, unilateral action by the Lao PDR may well result in dam construction by the other nations who will likely see little benefit in continued cooperation via the MRC; indeed, there are draft plans for a further 10 mainstream dams in the LMB. After an environmental assessment of these dams in general, and the Xayaburi dam in particular, the MRC called for a 10 year deferral of any decision of dam construction in the LMB, citing potential livelihood risks for over 2 million people. However, it is not clear whether this appeal will have any effect on the Lao PDR since it conflicts with the perceived national interest. Here, again, the tragedy of the freshwater commons is made evident, as one nation appears intent on pursuing a course of development that will reduce the value of the shared fishery resources of the entire LMB.

Conflicts over multiple uses of water by different stakeholders and interest groups can be difficult or impossible to resolve without mutual compromise. Even when agreement can be reached, only the water which remains after human needs have been satisfied is available to sustain ecosystems. Accordingly, nature often receives a manifestly inadequate share, as demonstrated by instances where flows of some of the world's great rivers (the Colorado, Nile, Indus, Ganges and Yellow rivers) have failed to reach the sea. Some external control must be imposed to ensure that water is no longer treated as a commons. If this is not done, the resource is monopolized by the most powerful human users, leaving little or nothing for weaker parties, or for nature. This, perhaps, is the real tragedy of the freshwater commons.

6.2. A global geography of river threat

A recent global analysis of threats to river health (see Box 6.2) underscores the consequences of conflicts over the freshwater commons, and the consequences of the scant consideration given to biodiversity in explicit or implicit decisions about water-resource management or water allocations (Vörösmarty et al. 2010). The analysis addressed threats to human water security (i.e. a reliable supply of clean water plus protection against floods) and threats to riverine biodiversity separately, since the impacts of a particular stressor will differ greatly depending on whether its effects are felt by river fishes or humans. For

Box 6.2

A global geography of river threat

A recent study by Vörösmarty et al. (2010) set out to map the aggregate effects of a range of threat factors and stressors (termed drivers) on human water security and freshwater biodiversity. The two analyses combined 23 weighted drivers within four categories as set out below to provide a global geography of threats to rivers (Table 6.1).

This list of drivers does not encompass all potential threats or stressors, in part because of the shortage of global datasets at a pixel-scale resolution of 0.5º (i.e. grids of 55.5 x 55.5 km), especially those relating to biotic threats; those concerning physicochemical threat are much better represented. Nonetheless, the range of drivers is wide and, incidentally, indicates the range of threats to rivers and their biodiversity (see also Table 6.2, page 139). Some drivers were routed downstream (if their effects were not inherently local) or divided by annual discharge (if their effects were subject to dilution), and all were weighted according to their relative impacts. The weightings assigned to each driver within each theme, and assigned to each theme, depended on whether their impacts were on biodiversity or on human water security. For instance, the weightings assigned to the number of dams and the extent of river network fragmentation in the context of human water security were quite different from their weightings in calculations of impacts on biodiversity, because dams can benefit humans but are detrimental to riverine biodiversity. Weightings assigned to other drivers that were detrimental for both humans and biodiversity, such as pollutants, also differed between the two analyses since, for example, high loadings of phosphorus and, especially, suspended solids,

Table 6.1: *Threat factors and stressors on human water security and freshwater biodiversity*

Category 1: drainage-basin disturbance	Category 3: water resource development (i.e. dams and flow regulation)
— Cropland area — Impervious surfaces — Livestock density — Wetland discontinuity	— Dam density — River fragmentation — Consumptive water loss — Human water stress — Agricultural water stress — Flow disruption
Category 2: pollutants	**Category 4: biotic threats**
— Soil salinization — Nitrogen loading — Phosphorus loading — Mercury deposition — Pesticide loading — Sediment loading — Organic loading — Potential acidification — Thermal alteration	— Number of non-native fish species — Percentage of non-native fish species — Fish pressure — Aquaculture pressure

are relatively more detrimental to biodiversity. In addition, the beneficial impacts of technological advances in engineering and regulatory approaches that enhance human water security were accounted for in order to map “adjusted” human water security; no such adjustment was possible for aggregate threats to biodiversity (for details, see Vörösmarty et al. 2010). Note that these analyses both summarise levels of relative threat to biodiversity and human water security; they do not demonstrate the actual status of human or animal populations as a result of these threats.

As is evident from Figure 6.2, rivers draining large areas of the Earth experience comparable and acute levels of threat. While sources of degradation in most rivers are similar, their engineered amelioration (included in the “adjusted” upper map in Figure 6.2), which emphasize treatment of the symptoms rather than protection of resources, reduces the imposed threat in Europe and North America. However, such technological fixes are either too costly for many other nations or have yet to be adopted. The reliance of some nations on costly technological remedies to safeguard human water security fails to address the underlying threat factors or stressors, and could thus be viewed as a source of water insecurity. In addition, a lack of comparable investments to conserve biodiversity account for the observed declines in freshwater species globally, even in those

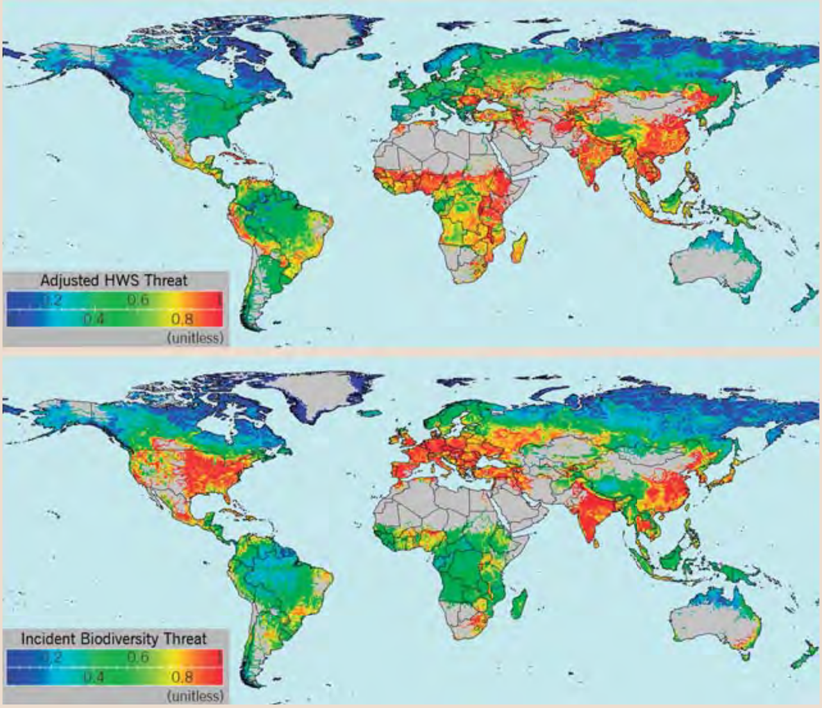

Figure 6.2:
A global geography of river threat, showing the patterns of aggregate threat from a range of factors to – in the upper map – human water security (adjusted to account for investments in infrastructure related to water engineering and treatment) and – in the lower map – freshwater biodiversity. Areas shaded gray have no appreciable river flow

Source: www.riverthreat.net (see also Vörösmarty et al. 2010).

Box 6.2 ***(cont.):*** **A global geography of river threat**

countries where significant adjustments to ensure human water security have been made. Again it must be stressed that the lower map in Figure 6.2 shows only aggregate threats to biodiversity, and not the consequences for populations and species. The best current source of such data are species-level assessments in the IUCN Red List (IUCN, 2011) although, obviously, a comparable analysis showing the aggregate impacts of these 23 drivers would be desirable, and would certainly serve to highlight parlous global plight of riverine biodiversity. A related issue is the need to translate the results of such analyses into action and transformation of current practices of water management: that remains a major challenge.

instance, as mentioned above, the construction of a dam will benefit some human stakeholders and disadvantage others, whereas the effects on fishes – due to altered river flow and habitat conditions, blocked migration routes, and so on – are always detrimental. To give other examples, mercury deposition poses a greater threat to humans who are at the apex of the food chain, than it does to most freshwater plants and animals, whereas acid rain or thermal pollution (arising from water used to cool industrial processes) can have profound impacts on freshwater biodiversity, but negligible effects on humans. This means that the various threat factors must be weighted separately in each analysis according to their relative impacts on human water security or biodiversity.

A surprising outcome of the global geography of river threat is that the two analyses produced similar patterns: low levels of water human security and high endangerment of biodiversity are generally correlated (Box 6.2). However the match between the two is far from complete as Figure 6.3 shows, and there are significant areas of the world, mainly in Europe, North America and Australia, where threats to human water security have been ameliorated (by considerable investment in hard engineering solutions and water treatment) whereas biodiversity remains imperiled: thus conditions are “good” for humans and “bad” for biodiversity. Over much of the rest of the globe, and especially in densely-populated parts of the developing world, the spatial pattern of threats to human water security and biodiversity are remarkably congruent: conditions are “bad” for both humans and biodiversity (Figure 6.3). In places where there are relatively few humans, such as the Amazon, and the far north of Asia, North America and Australia, rivers experience generally low levels of threat (things are “good” for humans and biodiversity) but this state of affairs is increasingly the exception rather than the rule. Most notable, is an absence of places on Earth where human water security is at risk in the absence of any threats to freshwater biodiversity (Figure 6.3). In short, this global analysis reinforces the conclusion that the freshwater commons

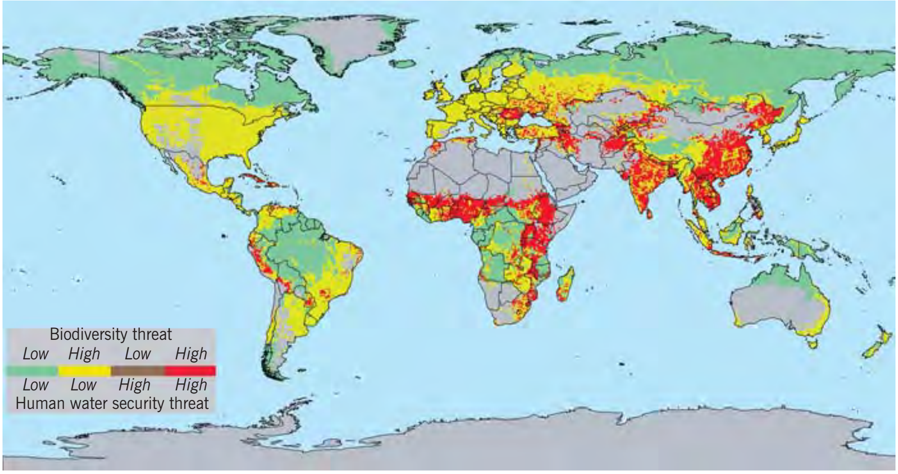

Figure 6.3:
A global geography of river threat, showing the patterns of spatial concordance of aggregate threat from a range of factors (see Box 6.2) to human water security and freshwater biodiversity. Especially striking is the lack of any localities where the threat to human water security is high and that to biodiversity is low. Areas shaded gray have no appreciable river flow

Source: www.riverthreat.net (see also Vörösmarty et al. 2010).

gives rise to state of affairs where human requirements for water invariably trump those of nature. Vörösmarty et al. (2010) do not take any account of the likely consequences of climate change for water availability in rivers, and some of the likely outcomes will be described below. Suffice to say here that climate change projections do not augur well for riverine biota in regions where the human footprint is pervasive, since this is where conflicts over water are likely to be most intense and, thus, the prognosis for biodiversity is especially bleak.

6.3. Principal threats to the freshwater commons

In the Anthropocene world, where many Earth-system processes are dominated by anthropogenic activities (see Chapter 1), we face a "pandemic array" of human transformations of the global water cycle (Alcamo et al. 2008), including changes in physical characteristics, and biogeochemical and biological processes in freshwater systems. These, together with rapid shifts in water use and withdrawal – such as a four-fold increase in demand for water over the last 50 years – are causing dramatic changes in patterns of water stress. The future health and sustainability of river ecosystems will depend upon how humans use water and manage drainage basins. The prognosis is not good. A significant proportion of the Earth's population (~0.9 billion people) does not have ready access to drinking water, and perhaps 40% (>2.5 billion) of people lack adequate sanitation (WHO/UNICEF 2008). The result is a parlous situation where child deaths attributable to contaminated water number around 5,000 *daily* (~1.5 million annually). Thus there is an unarguable imperative to improve access to water and sanitation for millions of people. This, among other things, will drive further transformation of the world's rivers.

The variety and number of threat factors and stressors included in the global geography or river threat study (see Box 6.2) indicate the potential for ecosystem degradation, but they represent a partial list comprising up of only those variables for which data were available at a global scale (Vörösmarty et al. 2010). These and others, such as extraction of river sand for use by the construction industry or the pollution arising from mining activities, have not been captured in that analysis, and nor, as indicated earlier, have the consequences of climate change. A more complete list of the panoply of such threats or stressor is given in Table 6.2. Irrespective of minor differences in the exact nature or relative intensity of threats to individual rivers, the general categories of such threats is fairly uniform the world over, as set out below:

- Flow alteration, water extraction and dam building
- Pollution of many types
- Degradation of floodplains and drainage basins
- Over-exploitation of fishes and other animals
- Invasive species (introduced or non-native organisms, including escapes from aquaculture)
- Climate change

Interactions among these threats or stressors give rise to combined effects that are difficult to predict: for instance, extraction of water for irrigation reduces the diluting effect that rivers can have on pollutants thereby amplifying the impact of the contaminant. Such interactions may be exacerbated by climate change: warmer temperatures and reduced river flows will likely increase the physiological burden of pollution on the aquatic biota, and biological feedback between stressors (e.g. climate change and nutrient pollution) may produce unexpected outcomes. Four of the five threat categories arise directly from the abuse of the freshwater commons since both over-extraction and contamination of water are in the interests of the individual but not the wider community of users. Drainage-basin degradation and habitat destruction are another aspect of the same phenomenon whereby individuals maximize the use of land for cultivation, grazing, timber harvest and so on. The exacerbating factor, in this instance, is that rivers are landscape receivers within drainage basins, and exhibit lateral connectivity with their surroundings. Under the influence of gravity, any increases in soil erosion, nutrient loads and contaminants that accompany land use change (including urbanization) are transported downhill into valley bottoms and hence rivers. Their landscape position not only makes rivers vulnerable to whatever changes occur within

Table 6.2: *Categories of threat to river ecosystems and a summary of their main characteristics and impacts on biodiversity. While this list is not intended to be fully comprehensive, the examples given include most major threats. Other categorizations are possible (see Table 6.4, p. 147): for example pollution, sand-mining and channelization could be grouped together under the shading of "instream habitat degradation", but the categorization is less important than the illustration of the variety of threats that rivers face*

Threat category	**Characteristics and examples**
Pollution	Broadly defined as something occurring in the wrong place, or at the wrong time, in the wrong (usually excessive) amount — Definition helpful as it avoids stipulating that a pollutant must be an un-natural or man-made contaminant; for example, rivers can be polluted by too much of a naturally-occurring nitrogen compounds, and not just by industrial effluents and toxic chemicals Origins may be "end-of-the-pipe" point sources or more diffuse — For instance, discharge from a factory or a mining operation versus run-off from agricultural land Pollutants may be organic or inorganic compounds, or a mixture thereof — Includes livestock waste and sewage (including pharmaceuticals), discharges from chemical factories or food-processing industries, seepage from landfills, oily runoff from roads and impermeable surfaces, agrochemicals (fertilizers or pesticides), and so on — Combined effects of mixtures of pollutants may be more damaging than individual effects, and have unexpected consequences Can include non-chemical alteration of environments in which pollution is not caused by a substance — Such as cooling water from power stations raising river temperatures (= thermal pollution), or increased suspended sediment loads associated with soil or river bank erosion Direct or indirect effects — Can act directly through toxicity or changes in acidity, causing mortality or sub-lethal fitness reductions, or indirectly by reducing dissolved oxygen levels resulting in respiratory stress
River regulation	Dam construction markedly alters flow conditions to which riverine biota are adapted — Changes flow upstream of dam; impoundment of standing water replaces section of flowing river — Alter flows downstream; natural flow regime replaced by pattern of water release determined by dam operations; in extreme cases, downstream flows may cease entirely for periods as dam (re)fills — Barriers to movement of organisms and material — Physicochemical characteristics of water (dissolved oxygen, temperature, sediment loads) up- and downstream of dam altered Channelization — River flow characteristics altered by channel straightening and constraints of "hard" concretized banks; increased rates of run-off in engineered channel — Levees or barriers prevent exchange of water with – and inundation of – floodplain — In extreme cases, natural habitat entirely destroyed as river channel replaced by channel with concrete sides and base

Table 6.2 *(cont.)*

Threat category	Characteristics and examples
River regulation	Flow reduction due to water abstraction — Over-abstraction of water for irrigation or other human needs reduce flows and, in extreme conditions, may result in dewatering downstream Water transfers between drainage basins — Change flow conditions in contributing and recipient rivers, and may lead to changes in water chemistry of latter; allow exchanges in biota thereby facilitating invasive species
Drainage-basin degradation	Urbanization — Impermeable surfaces dramatically increase magnitude and rates of run-off, and contribute pollutants of many sorts Agriculture — Runoff higher and faster than from natural vegetated land; runoff and groundwater seepage contains agrichemicals and nutrients from fertilizers or animal wastes; soil erodes from farmland during high rainfall events Changes in vegetation cover — Total or partial removal of natural vegetation alter run-off patterns and may be associated with soil erosion and instream sedimentation — Replacement of natural vegetation with different water requirements changes patterns of water supply from soil and run-off; may also alter types and amounts of organic matter (e.g. leaf litter and wood debris) entering rivers, as well as extent of shading and hence, river temperature
Over-exploitation	Reductions of fish stocks — Initially impacts larger or long-lived, late-maturing species, resulting in “fishing down” the food chain and exploitation of smaller, faster maturing species — The use of destructive fishing practices such as poisons, or of electricity and fine-meshed nets, drive further over-exploitation and may be resorted to as large fish become increasingly scarce Reductions of frogs, water snakes, river birds and pearly mussels — Mostly exploited as a source of food, especially in Asia, where the largest freshwater snake “fishery” in the world occurs at Tonlé Sap Lake, Cambodia — Birds that colonially nest in floodplain or riparian forest, or on sand bars in rivers, vulnerable to collection of eggs or nestlings for food — Pearly mussels are exploited for food and formerly also for their nacreous shells and pearls Reductions of crocodiles and turtles — Some exploitation for food, but other valuable products include the hides of crocodiles and shells or flesh of turtles that are used in traditional Chinese medicine; increasing scarcity of target species drives up their value and stimulates further exploitation — Growing prosperity of China has led to import of turtles from all parts of globe (especially other parts of Asia) to supply demand for medicines or tonics

Table 6.2 *(cont.)*

Threat category	**Characteristics and examples**
Over-exploitation	Collection for global pet trade — May affect some fishes and herpetofauna, as rare or wild-caught specimens can fetch high prices Sand mining — Sand or alluvium is widely-used to make concrete for building, leading to destruction of river habitat
Non-native species	Impacts depend on identity of introduced invader and the receiving community — Carnivorous species especially problematic for native prey with no specific anti-predator adaptations; similar impacts on aquatic plants may also occur if voracious herbivores become established — Competitive interactions for food or space may result from interactions with invasive species — Invasive species may change habitat conditions making them less suitable for native species — Non-native species may introduce diseases to recipient communities — Hybridization may occur if there is a close evolutionary relationship between non-native and native species
Synergistic impacts	Threat factors and stressors will not act in isolation, and their combined effects may be hard to predict, and greater than the sum of their individual impacts — Water abstraction by humans will reduce the capacity of rivers to dilute pollutants — Flow regulation and, for example, pollution change habitat conditions that may favour invasive species; drainage-basin degradation further alters river conditions facilitating invasion — Pollution and habitat degradation may limit ability of populations to recover from or compensate for human exploitation — Overexploitation and population reduction of native species may provide opportunities for establishment of invaders
Climate change	Impacts arising from rising temperatures and long-terms shifts in rainfall patterns, as well as medium-term effects such as glacial melt, and increased frequency of extreme climatic events — Higher temperatures will mean greater water use by plants (crops, pasture and natural vegetation) and thus more water abstraction for irrigation — Conditions in rivers may no longer be favourable for species that evolved there; opportunities for dispersal to suitable habitat may be limited — Human adaptation to a more uncertain climate is likely to encourage dam construction for water storage, flood control and hydropower, thereby magnifying impacts of flow regulation on biodiversity — Altered river flows (increased floods and droughts) will interact with all the threat factors above, while warmer temperatures may increase the toxicity of pollutants, leading to further uncertainty about the severity of their combined impacts

the drainage basin. They are also downstream transmitters of the material they receive so that human impacts do not remain local within a particular section of river. The hierarchical architecture of rivers and their tributaries which ensures that this transmission takes place increases the vulnerability of biodiversity throughout the network.

This longitudinal dimension of river connectivity is also evident from the impacts of dams on habitat conditions downstream. Dams also "smooth out" flow variability and limit floodplain inundation, both of which are essential components of healthy rivers to which the flora and fauna are adapted and upon which their life cycles may depend. Other impacts include the impediments dams cause to migrating fishes, and the entrainment of organic material, sediments and nutrients that sustain habitats and food webs downstream. Dams have led to the elimination of salmon runs in northwest Europe as well as along the west and (especially) eastern coasts of the United States (Limburg and Waldman 2009); the impact is especially severe when it occurs in association with a targeted salmon fishery. Less well known are the impacts on other migratory species, including those that move between rivers and coastal waters (shad, alewives, sturgeon and eels), and the many potamodromous fishes that undertake breeding migrations within river systems such as the Amazon, Mekong (see Box 6.1) and many others. Paradoxically, then, the longitudinal connectivity of rivers that ensures that insults can be transmitted throughout the system – thereby increasing the vulnerability of aquatic biodiversity to human impacts – is a feature essential to ecosystem health, since the migrations of animals and transport of materials depends upon it.

Another manifestation of the tragedy of the freshwater commons is overexploitation of fishes and other animals (mainly turtles, frog and crocodiles) since it is in the short-term interests of the individual to capture yet one more fish now rather than leaving it in the river where it would contribute to the sustainability of the fish stock. Climate change is likewise a consequence of human misuse of the global atmospheric commons, and the inability or unwillingness of individual states (and even individual citizens) to limit carbon emissions. Of the five threat categories or stressors, the effects of invasive species is the only one that does not involve treatment of fresh water as though it were a commons, but it can, nevertheless, interact with threat factors that fall into that category. Disturbed or degraded rivers are more susceptible to invasion by non-native or alien species than intact systems (see also Chapter 8), and they, together with reservoirs and man-made lakes created behind dams, can serve as stepping stones for the spread of invaders to other water bodies. The ongoing global epidemic of dam construction and fragmentation of rivers by impoundments (Nilsson et al. 2005) not only has direct effects on biodiversity through changed flow and habitat conditions, but also facilitates invaders and their impacts on native species by way of predation, competition and so on.

6.4. Understanding the intensity of threats to riverine biodiversity

The global geography of river threat described above is an alarming illustration of the prevalence of human impact on these fresh waters attributable, in large part, to their use as a commons. The range and variety of threat factors or stressors is also noteworthy. But the implications of this state of affairs for humans and biodiversity, and its seriousness, stem from a specific attribute of fresh water, especially water in rivers: its absolute scarcity. As described in Chapter 1, liquid fresh water covers less than 1% of the Earth's surface, and the amount habitable by animals constitutes only 0.03% of the total global water volume and mainly resides in lakes; the amount in rivers and streams is a mere 0.0002% (or 0.006% of all fresh water): a standing volume of 2,120 km^3 (Shiklomanov 1993). This tiny fraction in rivers is the source of most water used by humans.

Estimates of human appropriation vary somewhat, but current withdrawal is slightly over 50% of the accessible surface water supply or "available runoff" of approximately 12,500 km^3 (Chapter 2). Estimates of the proportion withdrawn – e.g. 54% is widely quoted – are sensitive to assumptions about how much of a river or its flow can be regarded as accessible (e.g. rivers in far northern latitudes are mostly untapped), or available for capture (typically floodwaters are not), and to the magnitude of total global annual runoff (probably ~40,000 km^3). Given that the Earth's population has recently topped 7 billion, and can be projected to reach 9 billion by 2050 or thereabouts, the intensity of competition for water between humans and nature must inevitably increase, raising concerns that planetary boundaries for sustainable use of this resource may be overstepped in the foreseeable future (Rockström et al. 2009). Such competition for water is always highly asymmetric: as human requirements for water go up, that which remains for nature declines; the converse is *never* true.

One driver of competition, among others (see above), will be the demand for water to grow food for the additional humans. Agriculture already accounts for roughly 70% of water withdrawals and, while only around 15% of global croplands are irrigated, they yield half of the saleable crops. Given that the extent of arable land is finite (and limited), bringing a greater proportion under irrigation may be the most expedient approach to feeding the 2 billion additional people expected by 2050, and improving the nutritional status of the many who are presently undernourished. This will further diminish the volume of water remaining for nature, a situation that will be exacerbated by shifts towards diets incorporating more animal protein because approximately twice as much water is needed to produce an American diet than a vegetarian diet of equivalent calories. One estimate is that food security needs could result in of water for irrigation consumption increasing by up to 50% over the next 20 years (Rockström et al. 2009).

To make matters worse, fresh water is not only a scarce resource: fresh waters are also hotspots of biodiversity. 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 (over 18,000 species) of all vertebrates (Dudgeon et al. 2006; Balian et al. 2008). The latter are mainly fishes, but also comprise the entire global complement of crocodilians, virtually all of the amphibians, and most of the turtles. Many of these are semiaquatic, and include species confined to riparian zones or adjacent floodplains (Dudgeon et al. 2006). Moreover, despite the much greater area and total production of marine environments, fish (Actinopterygii) species richness in the seas and fresh water is similar (14,736 and 15,149 respectively), with all of the saltwater species derived from a freshwater ancestor (Carrete and Wiens 2012). Some freshwater vertebrates are, of course, associated with lakes rather than rivers. Nonetheless, the fact that almost 10% of the Earth's animal biodiversity is associated with a relatively tiny amount of fresh water covering less than 1% of the planet's surface, stands in stark juxtaposition to ever-growing human demands for water which sustains that diversity. Indeed, Marshall McLuhan's catchphrase "the medium is the message" serves as uncomplicated summary of the essential threat to riverine biodiversity.

A further complicating factor is that most freshwater species have limited dispersal abilities, and their habitats are aquatic "islands" set within a terrestrial matrix. Fish typically are unable to move between rivers since they cannot tolerate salinity sufficiently well to migrate along the coast nor can they travel overland and surmount terrestrial barriers between drainage basins. Amphibiotic animals, such as frogs and aquatic insects, which have aquatic juveniles and terrestrial adults, enjoy more scope for dispersal over land. However, mayflies, caddisflies and most other stream insects (with the exception of some dragonflies) are weak fliers or habitat specialists, as are many amphibians, and their ability to traverse the terrestrial landscape is limited. Because of the limited faunal exchange between river basins, and the insular nature of inland waters, there is a considerable degree of local endemism (high α-diversity) and the inhabitants often have small geographic ranges, resulting in high species turnover (β-diversity) among river basins. Effective barriers to dispersal may explain the relative richness (in per unit-are terms) of fishes in freshwater habitats (Carrete and Wiens 2012), and have an important implication for biodiversity conservation. Individual river basins (especially those in latitudes unaffected by recent glaciation) are often not "substitutable" in biodiversity terms, and thus protection of one river does not ensure preservation of a representative portion of the regional species total (γ-diversity). To put it another way, loss of a species from a single river could, in effect, represent global extinction. This is markedly different from the relatively localized effects of most human impacts in terrestrial landscapes. Because rivers serve as receivers and transmitters of human impacts, are insular, and have drainage networks with a hierarchical structure, insults from upstream can travel throughout the system with the potential to imperil aquatic animals downstream.

6.5. The next great extinction?

Freshwater biodiversity is in a state of global crisis with freshwater species generally far more imperiled than their terrestrial counterparts (see reviews by Dudgeon et al. 2006; Strayer and Dudgeon 2010). Population trend data compiled by WWF since 1970 indicate that declines in freshwater species are considerably greater than those on land (Loh et al. 2005), especially in the tropics (WWF 2010), and the IUCN Red List (www.redlist.org) reveals that a host of freshwater species are extinct or imperiled (Table 6.3).

	Fishes	**Frogs**	**Reptiles**	**Mammals**	**Decapods**	**Bivalves**	**Dragonflies**
Number assessed	5,719 (2,912)	5,609	338 (3,226)	145 (5,404)	1,864 (250)	428	2,654
Threatened species (%)	30 (7)	30	37 (24)	40 (22)	19 (0.4)	38	10
Data deficient (%)	18 (20)	26	11 (17)	13 (15)	40 (35)	17	30

Note: Fishes = Actinopterygii; Frogs = Anura; Decapods = crayfish, freshwater crabs and shrimps.

Table 6.3:
Threatened freshwater animal species and, where relevant (in parentheses), their terrestrial (reptiles, mammals) or (fishes, decapods) marine counterparts, as indicated by an analysis of the IUCN Red List (version 2011.2). Data are percentage of extinct, critically endangered, endangered or vulnerable species out of the total number assessed. The proportion of species classified as data deficient is shown also. Marine bivalves have not been included, as only 30 species have been subject to IUCN assessment

A recent analysis argued that human activities have transgressed planetary boundaries for terrestrial and marine biodiversity, with species losses at least one to two orders of magnitude in excess of background extinction rates derived from the fossil record (Rockström et al. 2009). Assuming this is correct, we must also have far exceeded whatever margins would have been sustainable for freshwater biodiversity. Moreover, inadequate knowledge of tropical freshwater biodiversity (Balian et al. 2008) – especially among invertebrates – means that the extent of threat may be even greater. For example, fully 30% of all species of frogs and toads are at risk, but another 26% of these animals are classified by the IUCN as data deficient (DD), indicating that there is insufficient information on their distribution and abundance to make a reliable conservation assessment. In some such cases, it is very likely that an absence of records may well represent records of absence, and those DD species are likely to be gravely endangered. Significantly, the DD categorization in the Red List carries the caveat that if the range of a species is circumscribed and a considerable period has elapsed since it was last recorded, threatened status may well be justified. Among other groups of freshwater animals (Table 6.3), reptiles, mammals and decapods include more threatened species than their terrestrial or marine counterparts, and decapods and dragonflies include a high proportion of DD species. Assessments for many animals groups are far from complete: for instance, only 30% of fishes and 35% of reptiles have been assessed. Nonetheless, a striking finding is that almost 50% of freshwater animals assessed (20,524 species) by the IUCN are threatened (25%) or data deficient (23%); the equivalent total number for terrestrial animals (30,340 species assessed) is 36% (23% threatened and 13 % DD); for marine (6,414 assessed) it is 27% (14% threatened and 23% DD).

In intensively-developed regions, often those where the global geography of river threat reveals that human requirements for water have been secured by investment in river engineering and water treatment, over one third of the species in some major groups are threatened, including 38% of the fish species in Europe and 39% in North America. Other notable examples of species declines (reviewed by Dudgeon et al. 2006) are large river fishes worldwide, Asian freshwater turtles, and the recent extinction of the Yangtze river dolphin, *Lipotes vexillifer*. To obtain an overview of the threats to riverine biodiversity, and compare them with the threats facing freshwater animal biodiversity in general as well as species in other realms, data included in the IUCN Red List (version 2011.2) can be analysed to determine the percentage of extinct, critically endangered, endangered or vulnerable species at risk from a particular threat factor. As Table 6.4 shows, species are generally threatened by two or more factors acting in combination (2.7 on average for riverine animals) with biological resource use (or overexploitation) comprising the major threat overall, and in rivers also. However, pollution (Chapter 5) is of almost equal importance as a threat to biodiversity in rivers, and is the major threat to freshwater animals in general, but is less important in other realms, especially on land. Agriculture and natural system modification are also important threats to rivers, as are commercial development and invasive species, with climate change currently perceived to be a less important threat to freshwater animals than to their marine counterparts (especially coral). While there are more threatened terrestrial species than freshwater species (and some of the terrestrial animals may be better be characterised as semiaquatic), the numbers of threatened species in fresh water, and

Threat categories	Rivers (freshwater)	Terrestrial	Marine	All realms
Biological resource use	18 (17)	23	24	21
Agriculture	15 (14)	24	3	18
Urban development	11 (11)	12	13	11
Invasive species and pests	11 (11)	11	14	11
Pollution	17 (18)	5	14	11
Natural system modification	12 (13)	8	3	10
Climate change	6 (6)	6	15	7
No. threatened species	2,893 (5,206)	7,022	897	11,150
Mean no. threats per species	2.7 (2.1)	2.3	3.0	2.1

Table 6.4: *Relative intensity of threats to biodiversity in rivers, and in marine and terrestrial realms, as indicated by an analysis of the IUCN Red List. Threats to species across all realms are shown also, as well as (in parentheses) threats to freshwater species in general (i.e. all inland waters). Data are percentage of extinct, critically endangered, endangered or vulnerable species at risk from a particular factor. Factors that threaten fewer than 5% of species in any realm (i.e. human intrusion and mining, both 4% across all realms; all other factors combined <1%) have not been included*

especially in rivers, is high relative to the area these habitats occupy: there are only around 2.5 times more threatened animal species in the terrestrial realm than in rivers, or 1.4 times more than in fresh waters as a whole. This finding is likely to be relatively robust as there is no reason to suppose that assessments of the conservation status of terrestrial animals are any less complete than those of freshwater species and, as mentioned above, almost half of all freshwater species assessed are either at risk of extinction or DD. Some threatened species are associated with two realms (e.g. salmon or sturgeon that migrate between rivers and the sea) and are represented twice in the calculations in Table 6.4, but these are unlikely to have influenced the outcome of the analysis of relative threat intensity. However, the threat categorization used by the IUCN notably affects the conclusions that can be drawn from Table 6.4, as it is both less detailed and more generalized than one applying to rivers alone (Table 6.2). For instance, logging is treated by the IUCN as a category of biological resource use, whereas dams and flow regulation represent modifications of natural systems, but are categorised separately from threats due to agriculture (including plantations, livestock rearing and aquaculture) or urban development which could both be considered as alteration of natural habitats. Since rivers are markedly affected by land use changes within their drainage basins, as well as in-stream modifications such as flow regulation, the IUCN categorization does not fully capture the variety and intensity of threats to biodiversity in rivers set out in Table 6.2.

Irrespective of the causes of species declines and losses, they will certainly have knock-on effects for other organisms: for instance, reductions in predatory species may “release” smaller prey from control allowing them to proliferate; conversely, reductions in prey species will have implications for the animals that feed on them. For instance, birds, bats and spiders that make use of riparian zones can be impacted by changes in river water quality that reduce the survival of aquatic insect larvae and hence the abundance of emerging adults that sustain terrestrial insectivores. Other impacts are also possible: depletion or annihilation of salmon runs by overfishing and dam construction sever the connection between the sea and headwater tributaries by way of which marine-derived nutrients are transported upstream by migrating salmon. The result is reduced productivity of streams and associated riparian forest because of the absence of nutrients that would normally be contributed by death and decomposition of the breeding salmon. Terrestrial species such as bears that feed upon migrating salmon can be affected also (see Chapter 10).

It may well be possible that loss of significant portions of riverine biodiversity will represent the first wave of the sixth mass extinction event in geological history that eminent biologists believe is now ongoing as a result of human transformation of the Earth system (Eldredge 2001 http://www.actionbioscience.org/newfrontiers/eldredge2.html). The extent of the declines and losses of freshwater biodiversity that have been documented is probably a reliable indicator of the extent to which current practices are unsustainable (Dudgeon et al. 2006), and demonstrate how human exploitation and impairment of rivers have outpaced our best attempts at management. To this can be added a substantial extinction debt (that is presently impossible to quantify) due to human actions that have been taken already that have reduced populations below levels from which they can recover (Strayer and Dudgeon 2009), as well as losses that occurred in the past that have been overlooked. One likely source of this debt is habitat fragmentation (e.g. by dams), which interacts with the insular nature of rivers and their geometry (see above), to reduce the viability and persistence of populations that may already be dwindling to extinction.

As the Anthropocene Epoch proceeds, trajectories of human population growth, water use and consequential environmental alterations are rising steeply (the “great acceleration”; see Chapter 1) and can be projected to continue in the near future, likely resulting in further extinctions and knock-on effects, placing riverine biodiversity under greater stress.

6.6. Imperiled river invertebrates: The pearly mussels

One group of animals that particularly well illustrates the vulnerability of freshwater fauna to an array of anthropogenic threats is the pearly mussels. These bivalve molluscs (part of the group consisting of mussels and clams) make up the order Unionioda, consisting of around 850 species in six families, the majority of which are placed in the Unionidae (Figure 6.4). All threatened freshwater bivalves (see Table 6.3) are pearly mussels, and 8% of them (32 species) are already extinct. Their vulnerability arises from their own inherent attributes, as well as their interactions with other species.

Pearly mussels are especially diverse in large rivers in China and in those parts of the United States that escaped glaciation during the Ice Age, but occur also in Southeast Asia and elsewhere; the tropical species are especially poorly known. Many species have confined distributions and a high degree of endemism compared to other invertebrates such as dragonflies and other aquatic insects that can disperse during the terrestrial adult stage. Even in relation to fully-aquatic animals such as fish, mussels are relatively immobile or sedentary. A restricted range is one of the main contributors to vulnerability of freshwater species

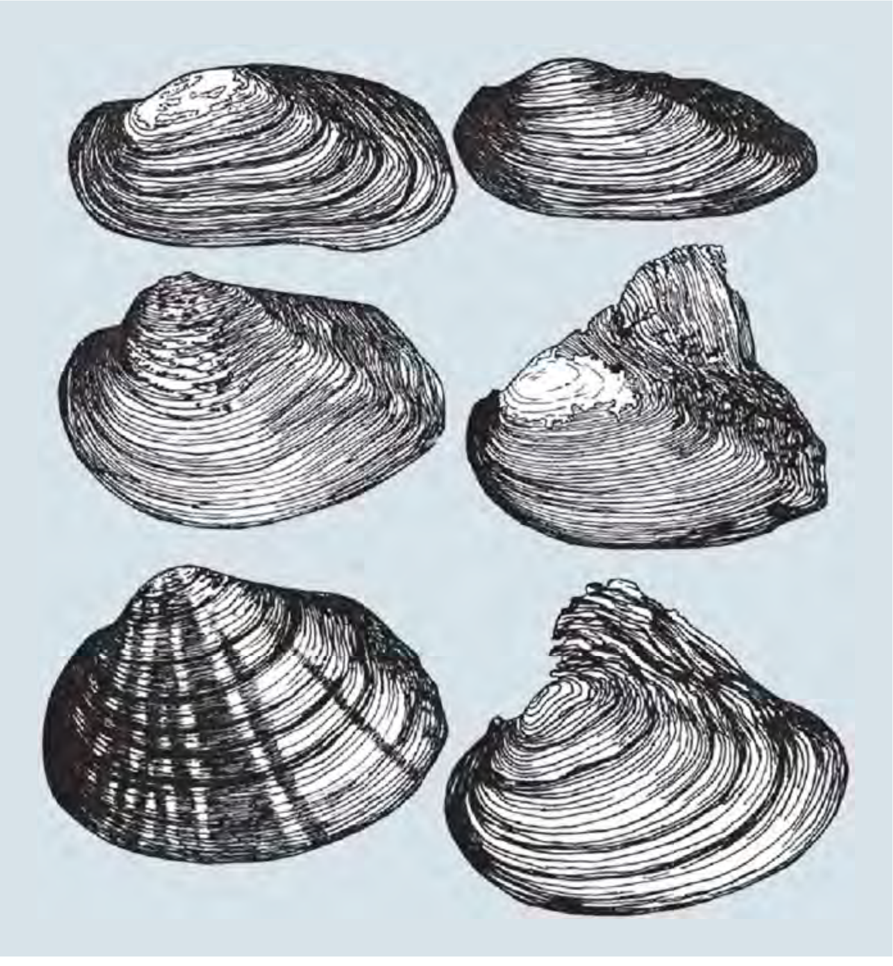

Figure 6.4:
Typical representatives of different pearly mussel (Unionoida) genera from China. The shell length of adults can vary from 3 cm up to almost 25 cm

since local degradation of their habitat can cause the loss of a population and may even result in global extirpation. Moreover, because they are filter feeders and burrow in sand and gravel of river beds, pearly mussels are acutely sensitive to water quality and sedimentation resulting from the wash-off of soil and silt from agricultural land. Flow modification or channelization that affect patterns of riverbed erosion and deposition also reduce habitat suitability for unionids.

Unusually for a freshwater invertebrate, many unionid populations have been depleted by human exploitation, driven by demand for their nacreous shells (Figure 6.5), the quest for pearls, or consumption of their flesh. In some parts of the world unionids are an important subsistence food, and rarer species may be taken as by-catch even if more abundant species are targeted. In the United States, mussels formed the basis of a substantial pearl industry beginning in the 1850s; around 10 species were involved, and as pearls were present in as few as one mussel in a 1,000, there was much mortality for little gain. Eventually, populations became overexploited and insufficient to sustain the industry, which collapsed in the 1900s (Humphries and Winemiller 2006). Beginning in 1890, a wider variety of mussels were collected and their shells used for button manufacture, but less than 20 years later, many larger species had declined and attention had shifted to smaller species. Some harvests seem astounding: in 1913 alone,

Figure 6.5: *An example of a large (24 cm long) unionid from Thailand showing the nacreous ("pearly") interior* (up) *shell valve and the worn exterior* (down) *valve*

over 13 million kg of shells were removed from living mussels in Illinois, and 100 million mussels were taken from a single 73 ha bed in the Mississippi River (Strayer 2006). Over-expoitation devastated the mussel fauna to such an extent that they have yet to recover, and the loss of a substantial biomass of filter-feeders must have had a significant impact on food webs and transport or transformation of suspended organic matter, phytoplankton and so on. While mussels no longer experience high levels of exploitation in the United States (due in part to the replacement of mussel-shell buttons by plastic substitutes in the mid-20th century), they drove the historic decline of many species so that – as with large river fishes – recollections of mussel abundance are subject to baseline shift (Humphries and Winemiller 2006). In parts of the lower Yangtze basin in China, however, a pearl "industry" continues, based on culture of a few relatively hardy species (mainly *Hyriopsis cumingii*, but *Cristaria plicata* and *Sinandonota woodiana* have been used) yielding virtually all of the global supply of freshwater pearls.

To make matters worse, since 1985, mussels in the eastern United States have suffered from competition with the non-native and highly invasive zebra mussel which has a relatively short life cycle and rapid growth *(Dreissena polymorpha)* leading to the extirpation of many populations, and this process may be driving already-threatened species to extinction. In this case the competition for filtered food is aggravated by the tendency of zebra mussels to foul or overgrow the unionids by attaching themselves to the shell of the larger mussels and the aggregate filtration rate of the attached individuals may greatly exceed that of their hapless host (Figure 6.6).

Figure 6.6:
Zebra mussels (Dreissena polymorpha) *overgrowing the posterior, siphon-bearing end of* Lampsilis siliquoidea *the United States. These invasive non-native mussels attach to pearly mussels and compete with them for food*

The multiple threats facing unionids have had the consequence that around 70% of the approximately 300 species of unionid in the United States are federally classified as in danger of extinction, with more than 10% perhaps already extinct due to human activities. Equivalent assessments from China have not been undertaken, but anecdotal reports suggest widespread declines in unionids. In addition to the impacts of pollution, habitat degradation, overexploitation and invasive competitors, one specific attribute of unionids places them at further risk: their life cycle. For most mussels and clams, the majority of which are sea-dwelling, reproduction is a simple matter. Eggs and sperm are released into the water, where they meet and fertilization takes place leading to a planktonic larval stage. Larvae feed on planktonic algae and develop until they are ready to metamorphose into a benthic juvenile. This lifestyle is not well suited for river-dwelling pearly mussels, in part because river currents might sweep planktonic larvae downstream and out to sea, and in part because river water contain much less algal food that the surface waters of the sea. Instead, pearly mussels depend on the presence of a suitable host to complete their life cycle. Females incubate fertilized eggs in modified gills (termed marsupia) where they develop into larvae called glochidia. The glochidia are expelled into the surrounding water and attach to the fins, gills or skin of a fish host (a few may also attach to amphibians or turtles). There, the glochidia live as parasites for several days or weeks (sometimes longer), whereupon they metamorphose into a tiny mussel and drop off the host to become free living on the river bed. While some unionids seem to rely on little more than chance, and the production of prodigious numbers of larvae, to locate a host, in others the margins of the flesh protruding from the shell of gravid females serve to attract potential hosts. Simple adaptations involve the use of contrasting colours along the tissue margins of gravid female mussels, but the lures may be expanded and elaborated (Figure 6.7) to resemble the shape and markings of a small fish bearing, in some *Lampsilis* species, a distinct eye spot. The resemblance is further enhanced if the lure sways in the current. The function of such lures is to attract the attention of other fishes in search of a mate or a meal, thereby greatly increasing the chances that larvae expelled at an appropriate moment, or released when the fish strikes at the lure, will locate a host. A similar system is used by *Villosa iris* but, in this case, the tissue margins are highly elaborated to resemble a small crayfish (Barnhart 2008). In the genus *Ptychobranchus* the glochidia larvae are released in groups encased within an ovisac (Figure 6.8A). The posterior end of the ovisac is adhesive, attaching to cobbles or stones, while the anterior portion waves to-and-fro in the current. Depending on mussel species, the ovisacs resemble potential prey items such as insects or larval fish. When an unsuspecting fish bites, the ovisac ruptures (Figure 6.8B) to release a cloud of glochidia (Figure 6.8C) that attach to

Figure 6.7:
The fish lure of Lampsilis cardium *mussels feature marked striping of the tissue margins, reminiscent of the markings of some species of North American* Notropis minnows *(Cyprinidae)*

the host's gills (Figure 6.8D). Among other adaptations to attract fishes is provision of edible clumps of sterile eggs to serve as a "bribe" for potential hosts (Barnhart 2008).

Figure 6.8:
A) Glochidia of Ptychobranchus subtentum *mussels are enclosed within 2 cm long ovisacs that resemble aquatic insects - in this case, blackfly pupae (Simuliidae). B) Glochidia are released in clouds when the ovisac is ruptured by, for instance, a fish bite. C) Glochidia (each ~0.2 mm long) prior to host attachment. D) Glochidia attached to the gills of a fish host*

This array of adaptations illustrate the essential point that pearly mussels cannot complete their life cycles in the absence of an appropriate host. And not just any fish host will do; many do not provide favourable conditions for glochidial development, while species-specific variations in glochidium morphology permit attachment to some types of hosts but not others. This presumably explains why mussels vary in the form and appearance of their adaptations to lure fish, and it is tempting to suggest that the more derived or highly evolved the lure appears then the more specific the most-parasite relationship can become. While there is not always a one-to-one relationship between fish host and unionid, the majority of pearly mussels depend on a few hosts only; in extreme cases the match between fish and mussel can be specific to a particular drainage basin. In any event, the parasitic larval stages of each type of mussel are constrained to a greater or lesser extent by the variety of available hosts. Reproductive failure need not involve complete disappearance of the preferred hosts: once encounters between glochidia and hosts fail to exceed some critical threshold, the probability of successful larval encystment, or the chance that a metamorphosed juvenile will drop from its host into a habitable patch of riverbed habitat, become too low to support recruitment of the next generation. While the ecological requirements of tiny mussel juveniles are not well understood, they are certain to differ substantially from those of the adults (e.g. with respect to sediment grain-size). Mussel vulnerability to anthropogenic impacts is consequently increased because habitat for populations of these animals must meet the requirements of all life stages.

Unionids are therefore directly imperiled by an array of factors, in addition to the indirect threats posed by others (e.g. dam construction, overfishing) that affect the distribution and abundance of their hosts. The more specific the host-parasite relationship, the more likely it is that impacts on the fish will be detrimental to the mussel. Despite their curious interactions with fishes (see also Box 6.3), and their species richness, it is difficult to bring conservation attention to bear on unionids since, like many freshwater invertebrates, they are non-charismatic – many species look quite similar, especially when the fish lures are not evident (Figure 6.4) – and have little contemporary relevance for most people.

6.7. Shifting baselines

Our imperfect knowledge of past conditions in rivers gives rise to “shifting baseline syndrome”. Most of the factors that threaten freshwater biodiversity today also acted in the past, although their scale and intensity has increased recently. Fish and other aquatic animals, such as beaver *(Castor canadensis),* Box 6.3

Pearly mussels and potential fish extinctions

A further complication in the relationship between fishes and pearly mussels arises from the fact that not only do the mussels parasitize fish and depend upon them, but the mussels are themselves an important link in the life cycle of certain fishes. Small carp-like Asian and European fishes known as bitterlings (~30 species, mainly in the genera *Acheilognathus and Rhodeus,* within the cyprinid subfamily Acheilognathinae) depend upon unionids as an egg repository, and are unable to reproduce in their absence. During the breeding season, females develop a long thin ovipositor that can be inserted between the shell valves in order to deposit eggs on the gills (Figure 6.9). The male releases sperm in the immediate proximity of the mussel and the sperm are carried into the shell and onto the gills – where the eggs are fertilized – by the feeding currents. The bitterling eggs and larvae are protected from predators as they develop, and compete with their filter-feeding host for food and oxygen. Free-swimming juveniles escape from the shell at three to four weeks of age. At least two species of bitterling are considered vulnerable by the IUCN. The plight of Japanese *Rhodeus smithii,* classified as critically endangered, is manifestly more serious, and Chinese *Acheilognathus elongatus* may even be extinct. Their decline has been attributed mainly to extirpation of potential hosts, although pollution and competition with introduced species are implicated also. Undoubtedly, bitterling dependence on pearly mussels for breeding makes them more susceptible to anthropogenic impacts than most other fishes. The plight of these fishes may provide a basis for building a compelling case for conservation of pearly mussels since the knock-on effects of mussel loss seem certain to include extinction of bitterlings.

Figure 6.9: *Male* (left) *and female* (right) *European bitterling* (Rodheus amarus) *showing the ovipositor used to deposit eggs within the unionid host*

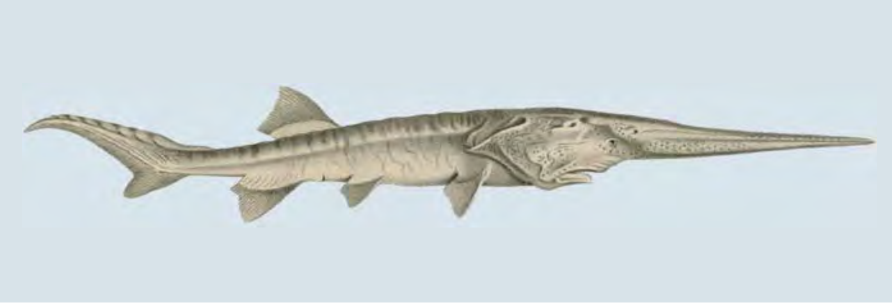

Figure 6.10: *The Yangtze paddlefish,* Psephurus gladius, *one of only two species in the family Polyodontidae. It is classified by the IUCN as critically endangered, but may already be extinct. Adults were reputed to grow to 7 m in length*

Figure 6.11: *The critically-endangered Yangtze sturgeon,* Acipenser dabryanus, *also known as Dabry's sturgeon, is confined to parts of the Yangtze upstream of the Three Gorges dam and appears close to extinction. It attains no more than 20 kg, much smaller than the Chinese sturgeon,* Acipenser sinensis *— also critically endangered — which occurs in the lower Yangtze and may weigh up to 450 kg and exceed 3 m in length*

have experienced historical declines since mediaeval times (around 1000 AD) in Europe, caused by a combination of siltation from intensive agriculture, increased nutrient loads and pollution, proliferation of mill dams, introduction of exotic species, over-fishing and hunting beaver (Hoffmann 2005). In the 17th and 18th centuries, these impacts were exported as migrating Europeans exploited those parts of the world that had hitherto been influenced only by indigenous peoples. Because these impacts occurred well before any stock formal assessments, they give rise to the false impression that conditions in the immediate past (or at the point when a human observer first begins to take an interest) reflect conditions in the intermediate and distant past: i.e. deception and a tendency to underestimate the extent of human impacts due to a shifting baseline (Humphries and Winemiller 2009). The shifting baseline is not just a matter of historic interest: large and charismatic species exploited by fishers can be affected by baseline shift within the span of a human generation; when these species are not encountered on a fairly regular basis, they are rapidly forgotten. This breakdown in expectation of what species should be present in rivers, and thus what needs to be conserved or restored, has been dubbed "ecosocial anomie" (Limburg and Waldman 2009). This point has been well demonstrated along the Yangtze river (Turvey et al. 2010) site of the recent extinction of the Yangtze river dolphin, and where extensive surveys have failed to detect any Yangtze paddlefish *(Psephurus gladius*: Figure 6.10) – the world's longest freshwater fish – or Yangtze sturgeon *(Acipenser dabryanus*: Figure 6.11) – and where the Chinese sturgeon *(Acipenser sinensis)* has become vanishingly rare. These large and charismatic species were rapidly forgotten by local communities as soon as they failed to be encountered on a fairly regular basis, offering a striking example of rapid cultural baseline shift within a human generation.

One implication of shifting baseline syndrome is that if people cannot remember what has been lost, or what conditions were formerly like in rivers, then it becomes difficult to manage these ecosystems in ways that will allow the recovery of already rare or threatened species. At the same time, target conditions for restoration of degraded systems have been forgotten. Furthermore, restoration of rivers back to their pristine state is no longer practical given the all-prevailing human footprint on most landscapes. Instead, it may be more realistic to plan for river rehabilitation where management is directed towards enhancing native biodiversity – that is, improving conditions relative to current baselines – rather than attempting to achieve a restoration goal that may prove impractical or unfeasible, prohibitively expensive and hence not societally acceptable. An example of rehabilitation of a riverine species, albeit one that was more an outcome of serendipity than advance planning, is given in Box 6.4. It illustrates the opportunities than may remain for conservation of near-extinct species that have been long forgotten by local communities.

Box 6.4

Back from the Brink

Père David's deer or milu *(Elaphurus davidianus)* is – or was – an inhabitant of swampy river floodplains in central and southern China (Figure 6.12). Milu are amphibious and strong swimmers, spending considerable time in the water as well as on grasslands and in reed beds; their hooves, resembling those of cows, are adapted to soft ground, and they graze a mixture of grasses and aquatic plants. Because of the productivity of the floodplain habitat, milu can reach 200 kg and are larger than the majority of terrestrial deer, and the males have large and many-branched antlers. Milu numbers were reduced, especially during the last 1,000 years or so, by habitat loss (due to conversion of floodplain to rice paddy) and hunting. By 200 years ago, they were approaching extinction, and the last wild individual was shot in 1939 (Jiang and Harris 2008).

Milu became known to western science in the 1860s through the observations

Box 6.4 *(cont.)*: Back from the Brink

of missionary Père Armand David. By that time, almost all of the remaining animals were part of a herd that had been maintained in the Royal Hunting Garden, by a succession of Emperors, for over 500 hundred years. A few of these milu were subsequently transported to Europe, which proved fortunate since a series of accidents and political upheavals in the late 19th and early 20th century resulted in the complete destruction of the imperial herd. Subsequent survival of milu was due to maintenance and captive breeding of descendants of the exported animals at Woburn Abbey in England. Although classified as extinct in the wild by the IUCN (Jiang and Harris 2008), milu from the English herd were sent to China in 1985, where there is now a substantial number of captive animals. Of greater importance is that two wild populations have since been successfully established along the Yangtze: the first at Dafeng Reserve (Jiangsu Province) in 1986 and, later, in 1993 at Tianezhou Reserve (Hubei Province). Both "reintroduced" populations have expanded considerably, and limits to the quantity of habitat set aside for them have led to incursions of milu from reserves into surrounding farm land. There are constraints upon how much habitat remains in which milu can range freely, but for now, it seems that this large riverine species has been rescued from the brink of extinction. Memories of this deer would have long-since disappeared as a result of cultural baseline shift along the Yangtze, and milu serve as a good example of how attempts at riverine restoration could be misled by overreliance upon recollections of what the ecosystem was once like.

Figure 6.12: Elaphurus davidianus

6.8. Climate change

Species loss from rivers may have been overlooked because baseline shift causes us to underestimate the extent of ecosystem degradation. The future seems likely to hold even more species loss from inland waters, as temperature, rainfall and runoff patterns alter as a result of global climate change. A point that will not have escaped readers is that such change is occurring precisely because humans have treated the Earth's atmosphere as a global commons, with individual nations unwilling to restrain their carbon emissions for the global good.

Human-caused climate change represents a profound and insidious threat to freshwater biodiversity (Table 6.2, p. 139), and thus it deserves special attention here. Signs of global climate change in freshwater ecosystems include detection of a direct carbon dioxide signal in continental river runoff records (Gedney et al. 2006), as well as warmer water temperatures, shorter periods of ice cover, and changes in the geographic ranges or seasonality of freshwater animals in temperate or higher latitudes (reviewed by Hein et al. 2009). Current projections are that temperature increases in the tropics will be less than those further from the equator, but the impacts of any rises in lower latitudes could be considerable since tropical *cold-blooded'* animals such as fish, amphibians, invertebrates and so on may already be close to their upper tolerance limits. There is an inverse relationship between temperature during growth and body size in amphibians and many aquatic invertebrates that results in smaller size at metamorphosis, plus decreased body mass due to increased metabolism at higher temperatures, and their combined effects reduce adult fitness. Shifts in the timing of fish breeding and migration (driven by alterations in temperature and/or flow and inundation patterns) are also likely, and warmer conditions could have serious consequences for reptiles such as turtles and crocodiles in which the sex ratio is determined by the temperature of the environment. Potential sources of physical disturbance and stress on riverine species include increased scouring and washout associated with snow melt and flood events, saline intrusion caused by sea-level rise in coastal areas, and the fact that the concentration of oxygen dissolved in water declines as temperature rises. Warmer temperatures and greater water use by terrestrial plants (and the need for more water for irrigation) may mean that some rivers that flowed year-round become intermittent. Climate change may pose further hazard by facilitating the establishment of alien species that threaten native biodiversity, and magnifying the toxic effects of some pollutants.

Because there has been insufficient research on the implications of climate change for freshwater biodiversity, especially in the tropics, the potential for adaptation to warmer temperatures is unknown for the vast majority of species. The best we can do is make extrapolations from the studies of temperate species (especially "cold-blooded" animals that have temperature-sensitive metabolic rates), which may allow identification of "winners" – species that may thrive under the changed conditions – and "losers" – those that fail to adjust and perish. Such extrapolation could, however, prove misleading for tropical species if, as pointed out above, they are already close to their upper tolerance limits. One prediction that seems likely to be robust is that the species most vulnerable to climate change will be those that are highly specialized, with complex life histories, restricted ranges or limited distributions, or highly-specific habitat requirements. The pearly mussels discussed above have most, if not all, of these attributes, and are sure to be placed at further risk by climate change. They will be climate-change "losers".

Freshwater biodiversity is extremely vulnerable to human impacts because almost 10% of the species known to science are concentrated in less than 1% of the Earth's surface area

Climate-change "winners" will be species that are generalist in their habits and habitat requirements, and have short generation times that will increase the possibility of rapid adaptation to changed conditions. But there may be other options allowing persistence. If, for the purposes of simplification, we assume that climate change only affects median water temperature of rivers, one option for species that lack the evolutionary capacity to adapt to rising temperatures (or cannot do so quickly enough) is to shift their distribution. For instance, animals in rivers could, conceivably, compensate for rising water temperatures by moving upstream to higher – and cooler – elevations or latitudes. This could be especially important for species in the tropics that are already close to their upper thermal tolerances and might be feasible for (say) fishes in north-to-south flowing rivers, although such movements would be subject to limitations imposed by river topography, the presence of dams or other in-stream barriers, availability of suitable habitats upstream, or some combination of these. However, the extent of movements needed to compensate for the upper bounds of the range of temperature rises predicted for the next century seem insurmountable for most freshwater species (see, for example, Bickford et al. 2010).

Given the insular nature of freshwater habitats, adaptation to rising temperatures by way of compensatory movements into cooler habitats further from the equator or to higher altitudes are often not possible, especially for the many fully-aquatic species that cannot move through the terrestrial landscape. Furthermore compensatory movements north or south are not possible where drainage basins are oriented east-west. Even flying insects and amphibians than can travel over land might find their dispersal opportunities limited in human-dominated environments. One conservation initiative that could help address this problem would be translocation or aided migration of threatened species from warming water bodies to habitats within their thermal range (Olden et al. 2011). Such actions would be controversial and costly, requiring detailed information about the species (currently available for only a tiny fraction of freshwater species imperilled by climate change), and pose the risk of ecological outcomes of the type associated with introduction of species to locations outside their natural geographic range. The argument that we should not move animals around so as to avoid causing unanticipated harm cannot be equated with adopting the "precautionary principle" because climatic shifts as the world warms may leave freshwater animals stranded within water bodies where temperatures exceed those to which they are adapted or to which they can adjust. Under these circumstances, doing nothing could result in more harm than that the potential risks associated with translocation.

In addition to the direct effects of climate change on freshwater biodiversity, human responses to such change could give rise to indirect impacts on biodiversity that will be as strong or even greater. Climate change will create or exacerbate water-supply shortages and threaten human life and property that will encourage hard-path engineering solutions to mitigate these problems (Palmer et al. 2008), including new dams, dredging, levees, and water diversions to enhance water security for people and agriculture and provide protection from floods so altering flow and inundation patterns in ways that will not augur well for biodiversity. In addition, there is increasing impetus to install new hydropower facilities along rivers to reduce dependence on fossil fuels and meet growing global energy needs. These engineering responses will magnify the direct impacts of climate change because they limit the natural resilience of ecosystems: for instance, by restricting the ability of animals to make compensatory movements to cooler conditions. A related problem is that hard-path solutions initiated in response to disasters (e.g. severe floods associated with rainfall extremes) may be permitted to circumvent environmental reviews and regulations because of the urgent need for project implementation. Offsetting some of the effects of dams will require that their operation be adjusted to ensure allocation of sufficient water to sustain ecosystems and biodiversity downstream. The need for implementation of these environmental flows is already pressing: one estimate is that dams retain over 10,000 km^3 of water, the equivalent of five times the volume of the Earth's rivers; the associated reservoirs trap 25% of the total sediment load that formerly reached the oceans (Vörösmarty and Sahagian 2000). This has had important consequences for rates of aggradation of deltas around the world, causing them to "sink" relative to sea levels and allowing upstream intrusion of salt water (Syvitski et al. 2009). This will exacerbate the effects of sea-level rise induced by climate warming and the consequences for freshwater animals in the lower course of rivers are unlikely to be favourable.

6.9. What is needed?

What can be done alleviate the tragedy of the freshwater commons? Or avert further damage and species declines? An obvious starting point is the necessity to raise awareness – at a variety of levels, from children to policy makers – of the remarkable richness of riverine biodiversity. To this must be coupled the many threats that these organisms face, and – as a consequence – the degree of endangerment that prevails. This primary task can be approached in a number of ways, but will require that we marshal sound arguments for that protection. It is one thing to enlighten people about the hidden or overlooked biodiversity of inland waters, and the extraordinary adaptations some of these animals have evolved (as in the case of pearly mussels, for example), but quite another to mount persuasive arguments for their protection. A fundamental aspect of the tragedy of the freshwater commons is that individuals must limit their own actions so as to maintain the communal good. In the Anthropocene world where conflicts over water are pervasive and likely to grow, limitations upon human activities intended to preserve biodiversity, and justifications of allocations of water for nature, will need to be extraordinarily persuasive. And, to reiterate, "the medium is the message": because fresh water is more limiting than the supply of land nor subject to comparable patterns of consumption and use, and because freshwater animals have far more restricted distributions than their terrestrial (or marine) counterparts, the conflicts between humans and biodiversity are exacerbated. How, then, can progress be made?

Two options seem possible, but these are not mutually exclusive, and other alternatives need not be ruled out. First, the argument for preservation of freshwater biodiversity can be made on utilitarian grounds: i.e. preservation of biodiversity is worthwhile for humans – hence we should limit our selfish degradation of the commons – because of the goods and services that more-or-less intact ecosystems offer. This point has been touched upon in Chapter 1: it suffers from the shortcoming that it is by no means evident that the services provided by river ecosystems (e.g. provision of clean water, flood control, and so on) require preservation of all the organisms present in those systems. There might be redundancy, such that certain species have no unique (or even apparent) function, and thus their loss can be substituted by others (Chapter 7). It might be argued that the supply of ecosystem goods, such as the yield of protein from capture fisheries, may be enhanced by maintaining rivers in near-natural states with intact food chains. This rationale has been (and is being) used in attempts to limit dam construction along the mainstream of the Mekong River (see Box 6.1, and further discussion by Dudgeon 2011) where there is a highly-productive fishery based on exploitation of a large number of species. But not all rivers sustain economically-valuable fisheries, or the fishery may be based on one or a few species. In such cases, managing the river for other uses (e.g. some combination of water supply, navigation, hydropower, and even waste disposal), or in a manner that favours productivity of the most desirable fishery species, may maximize net economic benefit even if it fails to bring about the best overall outcome for biodiversity.

Population declines in freshwater animals, and the proportion of species threatened with extinction, are far greater than their counterparts in the marine and terrestrial realms

One major obstacle to implementation of conservation measures for rivers is that scientists have yet to demonstrate convincingly that there is a strong linear relationship between biodiversity and ecosystem functioning – and hence the goods and services enjoyed by humans. This failure weakens any argument that all species must be conserved if ecosystem functioning is to be maintained (Dudgeon 2010; a detailed account of this matter is given in Chapter 7). In most cases, this failure deprives the conservation biologist of a utilitarian justification for the preservation of many elements of biodiversity or the protection of an intact ecosystem, although the potential detriment to the world's most productive freshwater fishery in the Lower Mekong Basin seems to be a possible exception to this generalization. The only remaining option, therefore, is to assert that freshwater biodiversity deserves preservation, in and of itself, because of its existence value. Such a stance arises from an ethical imperative and comprehension of the shared evolutionary history of all life on Earth. It could also be taken to encompass the inter-generational value that biodiversity could have for our descendants, to which could be added its option value in the broadest sense: i.e. direct uses that certain species may have for humans in future, or contributions – thus far unappreciated – made to ecosystem functioning. Unfortunately, many might argue that none of this offers sufficiently strong justification for prioritizing freshwater biodiversity conservation in light of human needs for clean water and sanitation, nor will it serve to satisfy the expectations of growing populations who wish to enjoy improved standards of living.

Clearly, better communication and raising awareness will be necessary to avert further degradation of the freshwater commons, but this alone will be insufficient. To advance the utilitarian argument for conservation (but not the ethical case), we need compelling evidence of, firstly, a positive relationship between biodiversity and ecosystem functioning. Secondly, the connection between freshwater ecosystem functioning and enhanced provision of goods and services for humans needs to be elaborated. The latter is needed because a utilitarian argument for preserving freshwater biodiversity so as to maintain ecosystem functioning depends on the notion that impaired function does, in fact, reduce the benefits gained by humans. The scientific priority is clear: elucidation of the links between biodiversity, ecosystem functioning, and the consequential benefits to be derived by humans.

Even in the absence of such information, there is much to be done. More research is needed to develop regionally-relevant hydro-ecological models that underpin allocations of water for nature; these environmental requirements must then be compared to the water needed to produce goods and services for society (Alcamo et al. 2008). That will allow identification of regions where conflicts between humans and biodiversity for scarce water resources will be most intense, and where conservation and management challenges should be addressed urgently. Much research on environmental flow allocations in rivers has already been undertaken, and scientists have a good understanding that maintaining the dynamic and variable nature of river discharge is a prerequisite for protecting freshwater biodiversity. This presents a formidable challenge given the context of a resource management paradigm aimed at controlling hydrological variability and enhancing predictability for humans, as well as the need to strike a balance between resource protection and development. Implementation at appropriate scales will be challenging also, but there have been some successes with modification of the operation of small dams to enhance downstream flow conditions. New and innovative strategies to develop regionally-specific environmental water allocations are being researched, and a new framework for flow standards developed by Poff et al. (2010) is evidence of recent progress.

Pearly mussels are threatened by reductions in water and sediment quality, historical overexploitation, and by reliance on the presence of certain fish species to complete their life cycle

More must be done to develop action plans for the conservation of those species that have been categorised as threatened by the IUCN. Such plans would need to incorporate population and/or habitat management, and identify measures needed to protect the target species, as well as regular monitoring. Attention also needs to be paid to data deficient species and their conservation status updated so that they can either be confirmed as currently non-endangered or, alternatively, become the subject of a targeted action plan. In addition to action plans, work is needed to determine which species are most vulnerable to climate change, and might therefore warrant conservation intervention, such as assisted translocation. At present, potential climate-change losers cannot be identified due to the paucity of ecological data on many freshwater species and their thermal tolerances. On a larger scale, it might be possible to identify the rivers that are most likely to be affected by climate change, such as those that are presently fed by glaciers, but taking measures that will alleviate the worst effects of such changes will be challenging as the failure to regulate global greenhouse gases emission to the atmosphere plainly demonstrates.

Another research topic where more work is needed is identification of variables for monitoring riverine biodiversity. The best variables would accurately represent the current status of biodiversity (or, at least, a subset of particular interest; e.g. fishes), and respond rapidly to environmental change; ease of measurement would also be a desirable attribute. Surrogate variables that indicate river health and hence are likely to be correlated with biodiversity may also be useful. Examples might direct measurements of water quality, in addition to some of variables listed in Box 6.2 (Table 6.1, p. 134), but such surrogates cannot fully substitute for direct monitoring of species richness and population sizes of species of particular conservation interest or societal relevance. Without long-term monitoring data, we will be in no position to ascertain whether and in what direction changes in river flora and fauna are taking place. Nor will we be able to assess the success or otherwise of measures to mitigate anthropogenic impacts, or management efforts to rehabilitate or restore river ecosystems. Furthermore, without a clear understanding of the relationship between biodiversity and ecosystem functioning (see above), it is unclear whether the effects of anthropogenic changes in rivers will be first manifest by structural alterations (shifts in species diversity and abundance) or by ecosystem functioning (productivity, nutrient dynamics, organic matter processing, and so on). Research into this topic, and the relationship between biodiversity and ecosystem functioning in general, is needed urgently.

Irrespective of the short-comings of current knowledge or inadequacies of research efforts, one thing is certain. Those interested in conservation of riverine biodiversity must take every opportunity to communicate what is known now about the threats to and endangerment of biodiversity, the value (however it is defined) such biodiversity has for humans, and the steps that can be taken to ameliorate, reduce or remove threat factors. Preservation of river ecosystems and the biodiversity they sustain will require the combined efforts of scientists, managers, politicians and other citizens. It is therefore essential that scientists share their findings, however incomplete they might be, so that they can be acted upon or implemented. The book you are now reading was written with that spirit in mind, and in the hope of ensuring that the Anthropocene epoch is not marked by a mass extinction of freshwater animals and the loss of many natural wonders.

6.10. References

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