16 Freshwaters: Global Distribution, Biodiversity, Ecosystem Services, and Human Pressures

Klement Tockner

Abstract

Freshwaters are among the most dynamic, diverse, and complex ecosystems globally. Lakes, rivers, and ponds cover about 1% of the Earth's surface; however, these systems contain 10% of all animals and one-third of all vertebrates. In addition, freshwaters provide a wide range of ecosystem services that are fundamental for human well-being, including clean water, recreation value, and food. At the same time, freshwaters are under immense human pressure due to overexploitation, habitat degradation, invasion, climate change, dam construction, as well as emerging stressors such as light, noise, and synthetic chemicals. Consequently, freshwater biodiversity is declining three to six times faster than biodiversity in marine and terrestrial realms, and ecosystem services are being eroded in unprecedented ways. Globally, wetlands have declined by 75% over the past decades, and out of 242 rivers longer than 1,000 km, only 86 remain free flowing. Hence, one-third of all freshwater species are currently threatened, and global freshwater megafauna populations even declined by 88% from 1970 to 2012. We need to carefully, and fundamentally, rethink future management strategies for freshwater ecosystems due to conflicting interests for conservation and exploitation. Freshwaters must be managed as hybrid systems, i.e., as a resource for human use as well as extremely valuable and diverse ecosystems. Furthermore, we must establish a blueprint of freshwater life to increase awareness about the enormous value of freshwaters and their rich biodiversity. Most importantly, however, we need to preserve the remaining free-flowing rivers, intact wetlands, and unspoiled lakes—for the sustainable benefit of humans and nature alike.

K. Tockner (✉)
Senckenberg Gesellschaft für Naturforschung, Frankfurt, Germany
e-mail: klement.tockner@senckenberg.de

Faculty of Biosciences, Goethe Universität, Frankfurt, Germany

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16.1 Freshwaters and Humans

The spread of humans across the globe was primarily driven by climate and access to water. Indeed, our human ancestors lived close to forests and trees (for shelter) and along the edges of lakes, rivers, and seashores (for resources). According to Finlayson (2014), *Homo sapiens* was an evolutionary response to the scattered distribution of water in time and space. Moreover, a key question is: Did water make people humans? Certainly, Finlayson (2014) makes a strong case. Other, more controversial, hypotheses worthy of mention are the aquatic ape hypothesis (Hardy 1960) and the waterside ape model (https://www.bbc.co.uk/programmes/b07v0hhm), which state that strong affinity to water affected the evolution of the ancestors of modern humans, who most likely were more aquatic than other apes. Recently, Cunnane and Stewart (2010) have emphasised in their "shore-based diet scenario" that there seems to be a close correlation between aquatic diet and human brain evolution.

Freshwaters (i.e., lakes, rivers, wetlands, and groundwaters) are pivotal for both nature and human well-being. People depend on freshwater as a resource as well as on freshwaters as valuable ecosystems. Human civilisations evolved along the shores of major rivers such as the Nile, Euphrates, Indus, Mississippi, or Huang He. Today, about 50% of the world's human population lives closer than 3 km to a surface freshwater body, and only 10% of the human population lives further than 10 km away (Kummu et al. 2011). Fang and Jawitz (2019) have assessed the coevolution of humans and water resources in the conterminous US between 1790 and 2010. They have demonstrated that humans had moved closer to major rivers in pre-industrial

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periods but moved farther away after 1870, reflecting the dynamic reliance on rivers for trade and transport in past times. Since industrialisation, humans have preferred areas overlying major aquifers, primarily due to the increasing accessibility to groundwater.

Globally, freshwater (as a resource) is unevenly distributed, both in time and space. Climate change, land-use alteration, and increasing human exploitation will further increase the pressure on water as a resource for human welfare as well as on inland waters as ecosystems, thereby intensifying the uneven distribution of freshwater—fostering conflicts between the exploitation of water and the conservation of freshwater-related ecosystems. Concurrently, the World Economic Forum's Global Risks Report (GRR) has listed water crises as among the top five risks in terms of impact for eight consecutive years (https://www.weforum.org/reports/the-global-risks-report-2019), and according to the World Health Organization, one in three people globally do not have access to safe drinking water (https://www.who.int/).

16.2 Freshwaters: Coupled Meta-Ecosystems

Freshwaters are unique ecosystems because they (i) form linear or mosaic landscape elements, embedded into the terrestrial matrix; (ii) are located at the topographically lowest points in the landscape and, therefore, integrate the various processes and pressures of the surrounding matrix; (iii) may rapidly expand and contract in area and/or volume; and (iv) are "open systems", which are vertically, laterally, and longitudinally connected to belowground, atmospheric, terrestrial, and marine systems. Consequently, freshwaters are among the most complex, dynamic, and diverse ecosystems on Earth. Given their unique position in the landscape, freshwater systems are particularly susceptible to the natural and human influences exerted by their surrounding terrestrial environment, both the immediately adjacent riparian zones as well as the entire catchment that they drain.

Landscapes, including freshwaters, are composed of interconnected ecosystems that mediate ecological processes and functions—such as material fluxes and food web dynamics—and control species composition and diversity. Freshwaters are closely linked to adjacent terrestrial systems through reciprocal flows of energy, materials, information, and organisms. On the landscape scale, these flows are controlled by the composition, configuration, boundary conditions, and linkages of individual ecosystem types, thereby forming what are known as meta-ecosystems (Gounand et al. 2018; Turnbull et al. 2018, and references therein). The relative importance of individual ecosystem types depends on the intrinsic properties of the landscape elements, or ecosystem types (ecosystem traits); the setting within the landscape; and the characteristics of the interfaces (e.g., shape, permeability) that control cross-system fluxes. For example, the juxtaposition of particular ecosystem types (i.e., their composition and configuration) may alter the magnitude of landscape processes as well as the directions of flow among ecosystem types (e.g., Marleau and Guichard 2019). The meta-ecosystem concept might be very helpful in landscape management, ecosystem design, and eco-engineering. It provides a framework for quantifying ecosystem diversity, a neglected component of biodiversity, and for testing its effects on genetic and species diversity, as well as the functional performance in coupled ecosystems (Harvey et al. 2020, and references therein).

Many freshwater systems, including river and cave networks, have a dendritic structure. These systems are not only hierarchically organised, but their topology and physical flow dictate the distance and directionality of dispersal and movement (Altermatt 2013, references therein). Furthermore, riverine assemblages are governed by a combination of local (e.g., habitat conditions) and regional (e.g., dispersal) processes. There is empirical evidence that the position within the river network (i.e., stream size) drives the composition and diversity of riparian plants, aquatic invertebrates, and fishes (for general information, see Turnbull et al. 2018).

Freshwater bodies are key biochemical reactors. Although they occupy only a small portion of the terrestrial land surface, freshwaters are pivotal ecosystems for the global carbon and nutrient cycles. Collectively, freshwaters respire ~40% and store ~20% of the 2.7 Pg of allochthonous carbon (i.e., carbon from outside sources), and denitrify or store ~60% of the 118 Tg of nitrogen they receive each year from terrestrial ecosystems (Cole et al. 2007; Aufdenkampe et al. 2011).

The master variables controlling ecosystem processes and biodiversity in freshwater systems are the flow and thermal regimes. Most recently, Wohl et al. (2015) have broadened the natural flow regime concept (Poff et al. 1997) and emphasised the role of sediment inputs, transport, storage, and interactions with water and plants. The sediment regime is critical for maintaining a shifting mosaic of aquatic and terrestrial habitats across entire succession gradients. Natural flow, sediment, and thermal regimes are required to maintain the ecological integrity of riverine ecosystems. Ecological integrity means the capability of a system to support and maintain physical, chemical, and biological functions and processes essential for ecosystem sustainability (Richter et al. 2003).

16.3 Global Distribution of Freshwater Systems

Although freshwaters are a very common feature of the land surface, we still lack accurate estimations of the global distribution of the various freshwater types (rivers, lakes and ponds, wetlands, groundwaters, and artificial water bodies). Indeed, it remains a challenge to calculate the spatial distribution, total area, volume, and residence time of freshwaters globally, primarily due to their dynamic nature, their diversity, and the manifold human alterations to which they are subjected.

In total, about 4.6 million km^2 of the land surface is covered by inland waters, corresponding to less than 1% of the total Earth surface (Downing et al. 2006). In addition, inland wetlands cover between 12 and 15 million km^2, corresponding to about 3% of the total Earth surface (Downing 2009). A sheer number of 304 million lakes and ponds cover a combined area of 4.2 million km^2. On the other hand, artificial ponds cover 77,000 km^2, with a strong upward trend. Messager et al. (2016) calculated that the median hydraulic residence time of all lakes is 456 days. They included 1.42 million lakes in their calculation, covering an area of 2.67×10^6 km^2 and with a total shoreline length of 7.2×10^6 km (four times the shoreline length of the oceans). The total volume of these lakes is 181.9×10^3 km^3, corresponding to 0.8% of the non-frozen terrestrial water stock.

Global estimates of the fluvial area (rivers and streams) range between 485,000 and 662,000 km^2. Hence, rivers and streams cover 0.30–0.56% of the global land surface (Downing et al. 2012). Moderately sized rivers (stream order: 5–9) comprise the greatest share, with less area covered by low- and high-order streams, while global stream length, and therefore the riparian interface, is dominated by first-order streams. Most recently, Grill et al. (2019) have calculated the total length of all rivers longer than 10 km. The total length is 11.7 million km, corresponding to 308,000 individual river segments. This number may increase by up to two orders of magnitude if first- and second-order streams are added. Concurrently, more than 50% of the global river network falls dry at the surface (i.e., intermittent rivers and streams). For example, dry rivers account for 94% of the river network of Arizona (USA), along with 66% of Californian streams and rivers (Levick et al. 2008). At the same time, the extent of intermittent rivers and streams and the duration of dry periods are rapidly increasing due to climate change, land-use alterations, and increased human water use (e.g. Datry et al. 2014).

Furthermore, a total of 500,000 reservoirs (larger than 1 ha) cover an area of 507,000 km^2. Their storage capacity is about 8,000 km^3 of water (Lehner et al. 2011). For comparison, the annual runoff of the Rhine River is about 60 km^3.

Fluet-Chouinard et al. (2015) have developed a downscaling method for inundation data (from Multi-Satellites, GIEMS) to produce a global inundation map. The total inundation area ranges from an annual minimum of 6.5×10^6 km^2 to a long-term maximum of 17.3×10^6 km^2, corresponding to a maximum of about 3.4% of the Earth's surface area, or 12.9% of the global landmass area.

Less is known about the global distribution and storage of groundwater. According to Gleeson et al. (2016), the total calculated volume of groundwater in the upper 2 km of the continental crust is approximately 22.6 million km^3, of which 0.1–5.0 million km^3 (average: 1.3 million km^3) are less than 50 years old—compared to about one-million-year-old groundwater in the Sahara region. The total young groundwater component corresponds to a $\sim$3 m deep water body across the global land surface. The global recharge of groundwater is calculated as $5–497 \times 10^3$ km^3 $year^{-1}$ (published estimates: $12–24.8 \times 10^3$ km^3 $year^{-1}$; see Gleeson et al. 2016, and references therein).

16.4 Freshwaters: Hot Spots of Biodiversity

Freshwaters are centres of global biodiversity, similar to tropical rainforests and coral reefs. Although freshwaters (excluding wetlands) cover less than 1% of the Earth's surface, they contain about 10% of all animal species, one-third of all vertebrate species, and 40% of all fish species globally (Table 16.1).

For example, there are about 16,000 fish species globally that spend all or part of their life in freshwaters. About 240 additional fish species are described per year (average value over the past 10 years), without any clear asymptotic tendency in total species increase. The Amazon, the Congo, and the Mekong Rivers jointly contain more than 1/3 of all freshwater fish species (Pelayo-Villamil et al. 2015). In Europe, the Balkan is a (freshwater) biodiversity hot spot of global importance. At least 200 native fish species are described for this region, of which 81 are listed as threatened. However, many species are listed as data-deficient, and the number of threatened species is most likely much higher as currently stated because many species still remain undescribed (Kottelat and Freyhof 2007).

Wetlands, including riparian zones, are keystone ecosystems for humans as well as biodiversity hot spots of

Table 16.1 Number of described species in surface waters (excluding wetlands) and in ground waters (after Balian et al. 2007; Stoch and Galassi 2010)

Taxonomic group	Surface waters	Groundwaters (Stygobionten)
Insects	75,908	18
Vertebrates	18,238	163
Crustaceans	13,054	3400
Other Phyla	7227	116
Arachnida	6149	650
Molluscs	4998	350
Annelida	1761	78
Total	**127,749**	**4775**

global importance. An inventory of the terrestrial fauna in Switzerland found that 85% of the regional species pool (a total of 4,036 species in 12 taxonomic groups) occurs in riverine floodplains, although they cover less than 0.3% of the country (Tockner and Ward 1999). The disproportionately high species richness in floodplains and riparian zones has been confirmed for mammals, birds, plants, or molluscs, and in many regions. In addition, there is empirical evidence that many terrestrial upland species seek temporary shelter in riparian zones during hot and dry weather conditions, further increasing the value of floodplains (and wetlands) as refugia for otherwise obligate terrestrial species. Hence, the conservation and restoration of floodplains and riparian zones must be given utmost priority. A natural flow regime, an unconstrained river corridor, and a dynamic sediment and large wood regime are required to maintain the high biodiversity characteristic of entire river corridors (e.g. Tockner and Stanford 2002; Naiman et al. 2010).

Wetlands are particularly species-rich ecosystems because they provide habitats to aquatic, amphibian, and terrestrial species. A comparison of seven globally important wetlands (Canadian peatlands, Florida Everglades, Pantanal, Okavango Delta, Sundarban, Tonle Sap, and Kakadu National Park) confirms high plant and vertebrate diversity, while information on invertebrates remains scarce (Junk et al. 2006). All seven wetlands are critical for long-distance migratory bird species. However, the number of endemic species remains low, except for the Everglades, primarily due to the high degree of connectivity with surrounding ecosystems. At the same time, human pressures are increasing in all major wetland types.

16.5 Ecosystem Services of Freshwater Systems

The benefits people receive from ecosystems, known as ecosystem services (ESS), contribute substantially to human health, well-being, and sustainability. Ecosystem services include provisioning (e.g., fishery), supporting (e.g., biodiversity), cultural (e.g., recreation), and regulating (e.g., carbon storage) services. Moreover, the importance of the ESS concept reframes the relationship between nature and humans, with humans as part of nature (e.g., Daily 2003).

Freshwaters provide a wide range of ESS that are of fundamental importance to human well-being, including clean water, food, water storage, and recreation value, among many other services. For 2011, Costanza et al. (2014) calculated a total value of US$ 145 trillion/year for all ecosystems combined, and a loss of ecosystem services ranging from US$ 4.3–US$ 20.2 trillion/year since 1997 due to land-use change. The combined value for tidal marshes, mangroves, swamps, floodplains, lakes, and rivers is US$ 38.7 trillion/year. However, the aerial estimation of wetlands and surface freshwaters in Costanza et al. (2014) is much lower compared to recent estimates (see above). Indeed, ESS (per area unit) provided by wetlands and surface waters are highest among all ecosystem types, except for coral reefs. Wetlands, for example, provide an average value of ESS of US$ 140,000 ha^{-1} $year^{-1}$—compared to US$ 4,900 ha^{-1} $year^{-1}$ for forests. The average value of ESS provided by lakes and rivers is three times higher than the value provided by grasslands (Costanza et al. 2014).

Floodplains are, in particular, hot spots for multiple ecosystem services, including flood mitigation, carbon sequestration, nutrient retention, and biodiversity (e.g., Tomscha et al. 2017). Indeed, the entire river corridor needs to be considered when managing floodplains for ESS and biodiversity. On the other hand, groundwater–related ecosystem services have been rarely quantified, despite the enormous role groundwater plays for human health and well-being. Griebler and Avramov (2014) have emphasised the lack of information on groundwaters as ecosystems, their spatial extent, and their degree of connectivity to other systems, food webs, and key processes, functions, and related and dependent ecosystem services.

The success of river restoration can also be assessed using the ESS approach. Comparisons across Europe have demonstrated a median value of total ESS for rivers of € 1,500 ha^{-1} $year^{-1}$; restoration almost doubled the total value of ESS (provisioning, regulating, cultural ESS) (Vermaat et al. 2016). For example, the restoration of the Emscher River and its tributaries (Germany), one of the largest and most challenging restoration projects globally (estimated costs: ~€ 5.3 billion), have created market and non-market values of about € 130 million per year. This is considered a minimum value because many services such as carbon sequestration and biodiversity have not been included in the calculation. Nevertheless, it demonstrates the possibility of using the ESS concept as a guiding principle in river restoration (Gerner et al. 2018). Indeed, a robust assessment of ESS is required to support the sustainable implementation of water and biodiversity policies. Ultimately, this implementation depends on the availability of data—for Europe, for example, a good and comprehensive data basis has been collated as part of implementing the EU Water Framework Directive.

Up to now, ESS have not been included in the calculation of national GDP and therefore have not been valued in the way they should be. Some of the ESS estimates are based on virtual, not real prices. We need to raise awareness of the value ecosystems provide, and the manifold losses due to ongoing and accelerating land use degradation, pollution, climate change, and fragmentation. At the same time, the economic calculation of ESS presents a key dilemma of an otherwise very valuable concept. Fu et al. (2014), for example, have listed hydropower as an important service provided by ecosystems. However, hydropower is a geosystem rather than an ecosystem service as discharge and slope are only required to produce energy. Similarly, navigation is not an ecosystem service; in fact, a natural system may even constrain navigation (and hydropower generation). In this context Bogardi et al. (2013) identified the water cycle as a fundamentally planetary service whereby ecosystems play a regulating role. Hence, we need to exercise care when applying the ESS concept because a purely economic calculation may lead to long-lasting harms to the biodiversity and other ESS freshwaters provide.

Unfortunately, ESS are, in most cases, restricted to provisional and supporting services, and only to a lesser extent to regulating services, and even less to cultural services. The economic valuation is becoming the dominant driver, with unwanted trade-offs for nature and humans (e.g., bioeconomy, green infrastructure, bioenergy). Moreover, benefits from ecosystems are more than just economic and monetary values. Indeed, we are currently witnessing a widespread domestication of ecosystems, particularly of freshwaters (Tockner et al. 2011). It means that these systems have been optimised for a few ESS that provide major, short-term economic benefits to humans, yet concurrently cause unforeseen changes in other ecosystem attributes. In its simplest form, domestication of ecosystems means that nature is exploited and controlled (Kareiva et al. 2007).

A key challenge is to link biodiversity to ESS. Do we require 80%, 60%, or just 40% of the contemporary biodiversity to maintain key ESS? The tight linkage between biodiversity and ESS—as it is the case in IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services)—may cause a potential threat to biodiversity because there is a risk that some ESS will be valued much above biodiversity. Overall, there remains a fundamental lack in understanding the long-term and large-scale relationships between biodiversity, ecosystem processes, and ESS.

16.6 Freshwater Ecosystems Under Major Threats

Today, humans are shaping our environment, and especially freshwater systems, in global, profound, and, in most cases, irreversible ways. The transformation of the Earth by humans can best be demonstrated by the distribution of biomass. Human and livestock biomass (in total, ~0.166 Gt carbon) is more than one order of magnitude higher than the biomass of all wild mammals combined (~0.0076 Gt carbon; Bar-On et al. 2018).

Freshwaters are under immense pressure due to overexploitation, pollution, habitat degradation, invasion, infectious diseases, and climate change. Reid et al. (2019) have documented 12 emerging threats to freshwater biodiversity that are either entirely new since 2006 (Dudgeon et al. 2006) or have since intensified: (i) changing climate; (ii) e-commerce and invasion; (iii) infectious diseases; (iv) harmful algal blooms; (v) expanding hydropower; (vi) emerging contaminants; (vii) engineered nanomaterials; (viii) microplastic pollution; (ix) light and noise; (x) freshwater salinization; (xi) declining calcium; and (xii) cumulative stressors (Table 16.2).

Lebreton et al. (2017), for example, have estimated that between 1.15 and 2.41 million tons of plastic debris enter the ocean per year from rivers, with the top 20 countries—mainly located in Asia—accounting for 67% of the total load. Furthermore, the major proliferation of synthetic chemicals—including pesticides—has not yet been included in most analyses of global change. Bernhardt et al. (2017) have reported a global production of 116×10^6 metric tons of N fertilizer, 38×10^6 metric tons of P fertilizer, and 6×10^6 metric tons of pesticides. Expenditures for pesticides amount to $29 billion per year, and global pharmaceutical consumption amounts to even $760 billion per year. The increase in synthetic chemical production is outpacing the other agents of global change such as habitat destruction and rising atmospheric CO_2 concentrations (Bernhardt et al. 2017). At the same time, data and knowledge about the

Table 16.2 (from Reid et al. 2019): Characteristics of emerging threats to freshwater biodiversity: geographic extent, severity of effects, potential ecological changes, degree of understanding, and potential mitigation options. For more details see: Reid et al. (2019)

Emerging Threat	Geographic Extent	Severity of Effects	Ecological Changes	Degree of Understanding	Mitigation Options
Changing climates	Global	Already causing extinctions; likely to cause more.	Alters species size, range, phenology and survival.	Moderately well understood but high unpredictability.	Global commitments; expand protected areas; restore thermal refugia.
E-commerce & invasions	Global *(primarily developed markets)*	Significant role in trade of nonnative plants and animals.	Creates novel modes of long - distance dispersal.	Largely unregulated activities that are poorly understood.	Online consumer accountability tools; awareness campaigns.
Infectious diseases	Global *(especially tropical systems)*	Already causing extinctions; likely to cause more.	Alters species survival, with clear ecosystem effects.	Increasingly well understood but high unpredictability.	Improve surveillance; management to favour ecosystem controls.
Harmful algal blooms	Global *(warm, nutrient -rich areas)*	Linked to species losses; likely to cause more.	Reduces species growth, survival and reproduction.	Increasingly well understood , some unpredictability.	Improve surveillance; management to favour ecosystem controls.
Expanding hydropower	Global *(primarily emerging markets)*	Already causing extinctions; likely to cause more.	Fragments river systems, inhibiting species movement.	Well understood , but interactive stressor effects unclear.	Ameliorate passage infrastructure; assess all project impacts.
Emerging contaminants	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Alters some species health, abundance and reproduction.	Largely understudied and thus poorly understood.	Improve medication disposal; advance wastewater treatment.
Engineered nanomaterials	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Causes minimal acute toxicity in some species.	Considerable uncertainty around long-term effects.	Improve detection and characterization; create targeted formulations.
Microplastic pollution	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Potentially detrimental effects on species health.	Considerable uncertainty around long-term effects.	Reduce plastic usage; enact legislation to curb use of specific products.
Light & noise	Global *(primarily developed markets)*	Linked to species disturbance; likely to continue.	Alters behaviour and physiology of some species.	Well understood, but ecosystem -level effects unclear.	Identify less harmful types; reduce usage; educate users.
Freshwater salinization	Coastal lowlands	Linked to species losses; likely to cause more.	Reduces species growth, survival and reproduction.	Increasingly well studied and understood.	Control point sources; strategic release of freshening flow.
Declining calcium	Softwater lakes	Linked to species declines; likely affecting foodwebs.	Causes shifts in lake invertebrate assemblages.	Increasingly well understood , but solutions unevaluated.	Further reduce acidic precipitation; replenish calcium in watersheds.

combined effects of synthetic chemicals, and the interaction with other anthropogenic stressors, remain in their infancy.

Hydropower dam construction is another major threat to freshwater biodiversity and ecosystem processes and services. Hydropower is a renewable but not an environmentally friendly or climate-neutral energy source. In 2016, 71% of renewable energy was from hydropower. In the US, 82,000 large dams and over 2 million small, low-headed dams have been constructed to date. Currently, more than 3,700 large dams are either planned or under construction globally, further fragmenting the remaining free-flowing rivers. At the same time, we are observing a major shift in dam construction towards the Global South (Zarfl et al. 2015). Indeed, the same problems we have faced in Europe, North America, or in Japan are being repeated in the Global South, regarding the multifold consequences of large dam construction on both humans and nature. For example, the cumulative effects of dams are practically unknown because careful environmental assessments are lacking. In addition, we need to include climate change into the planning due to anticipated alterations in the flow regime and therefore energy production. We also need to be very cautious in not overestimating the benefits and underestimating the costs—unfortunately, a common strategy in megaproject planning and design (Tockner et al. 2016; Moran et al. 2018).

While large dams are mostly being planned and constructed in the global South, we are seeing a boom of small hydropower plants in large parts of Europe, despite the European Water Framework Directive, with its key aim not to deteriorate the ecological status of their waters. Let´s take Austria as an example: two-thirds of its total electricity is produced by hydropower. There are already 2,900 hydropower plants in operation, which feed electricity into the public grid (Wagner et al. 2015). However, 84% are small hydropower plants, contributing less than 5% to the total electricity produced. Less than 15% of the rivers and streams are remaining in a good ecological status. At the same time, about 350 hydropower plants—mainly small facilities—are planned, under construction, or have recently been finished.

Two-thirds of these plants are located in critical zones, i.e., in protected areas or along rivers and streams with at least a good ecological status (Wagner et al. 2015). Indeed, the cumulative effects of small hydropower plants, and their interactions with other stressors, are rarely considered in planning, in Austria as well as globally (Lange et al. 2019), albeit the fact that the environmental footprint per MW is most likely higher for small than large hydropower plants. Ziv et al. (2012), for example, have demonstrated how dam configuration can minimise the harmful effects on fish while still producing high levels of hydropower.

Dams are responsible for the high degree of fragmentation of rivers and streams. A recent study has demonstrated that out of 242 rivers longer than 1,000 km each, only 86 rivers remain free flowing (Grill et al. 2019). The free-flowing rivers are mainly restricted to the Arctic region as well as to the Amazon and Congo Basins. In SE Asia, only two long rivers remain free flowing, namely the Irrawaddy and the Salween. Assuming the completion of all large dams planned and under construction, the river flow volume already affected by dams would almost double (Grill et al. 2015, 2019). In Europe, the free-flowing Tagliamento River (NE Italy) and Vjosa River (Albania) are reference ecosystems of continental importance. Otherwise, only small remnants of free-flowing rivers and streams remain. Concurrently, in the US and in Europe, dam removal is increasing in importance (O'Connor et al. 2015), with the Glines Canyon and Elwha River (USA) as well as the planned Sélune River (France) dam removal projects as the largest in North America and Europe, respectively.

While we are fragmenting rivers longitudinally, we are connecting river basins and even entire continents laterally. In Europe, for example, 28,000 km of navigable canals and rivers are creating a pan-continental ecoregion, leading to an increasing homogenisation of freshwater fauna. While contemporary fish richness is higher—compared to the historic state in the mid-nineteenth century—in all major catchments assessed (251 European catchments larger than 2,500 km^2; average net gain: 5.7 species per catchment), this gain is mainly due to the introduction of exotic and the translocation of non-native species (Sommerwerk et al. 2017).

Dams and water transfer projects are considered as suitable engineering solutions to meeting increased water demands, while water distribution is becoming more uneven due to climate change, land-use alteration, and direct human exploitation—both in time and space. For example, during the coming decades, we may expect a nine-fold increase in the volume of water transferred across basins—and even continents. At present, 34 water transfer megaprojects exist, and 76 megaprojects are either proposed, planned, or under construction (Fig. 16.1). These future projects, if realised, will transfer 1,910 km^3 of water per year, corresponding to the total volume of about 30 Rhine Rivers, across a total distance of 80,400 km (Shumilova et al. 2019). Hence, water transfer projects must be included in global hydrological models, and internationally agreed criteria must be established to assess the social, economic, and ecological consequences of these megaprojects.

Wetlands, including floodplains and delta regions, are highly threatened ecosystems. Davidson (2014) has compiled 169 reports of historical wetland loss and calculated a decline between 69 and 75% in the twentieth century (coastal wetlands: 62–63%). Of the remaining wetlands, only 11.3% are protected (Reis et al. 2017). This study also emphasizes that terrestrial protection does not adequately protect freshwater systems. Indeed, high human impacts, even in protected areas, underscore the urgent need to maintain and restore wetlands, their immense biodiversity as well as the fundamental services they provide for humans.

River deltas and floodplains are wetland ecosystems of global importance, for both humans and nature. Worldwide, 500 million people live in deltas, including megacities such as Dhaka, Bangkok, and Shanghai. In fact, humans are fundamentally altering the functioning of deltas on the global scale due to the truncation of sediment inputs, raising sea water levels as well as naturally high subsidence rates, which are further exacerbated by human activities. The Nile and the Indus Rivers are carrying 98 and 94% fewer sediments today, respectively. The Rhone and the Danube Rivers are carrying 85 and 60% fewer sediments, too. And one-fifth of the Indus delta plain has been eroded since the river was dammed in 1932 (e.g., Syvitski et al. 2009; Giosan et al. 2014).

Along the 28 largest European rivers, floodplains (connected and disconnected) cover a total area of 470,000 km^2. These floodplains are home to 62 million people, who generate a combined calculated GDP of US$ 1.3 trillion per year (K. Tockner, unpublished data). This demonstrates the tight linkage between ecosystems and humans, but it also highlights the increasing risks to people and infrastructure, considering the higher probability of extreme flood events in the future due to climate change and land-use alterations.

As a consequence of the widespread and intense direct and indirect modifications of rivers and their basins, biodiversity and its related ecosystem services are being eroded much faster in freshwaters than in most other ecosystems. Indeed, freshwaters are among the most threatened ecosystems globally, and the decline in biodiversity is 3–6 times faster than in marine and terrestrial realms. In fact, one in three freshwater species is already threatened with extinction. Since 1970, freshwater species populations have dropped by 83% (Loh et al. 2005).

Charismatic freshwater megafauna (species > 30 kg) are umbrella or flagship species, representative of overall freshwater biodiversity (Fig. 16.2). Globally, freshwater megafauna populations declined by 88% from 1970 to 2012, with the highest declines in the Indomalaya and Palearctic realms

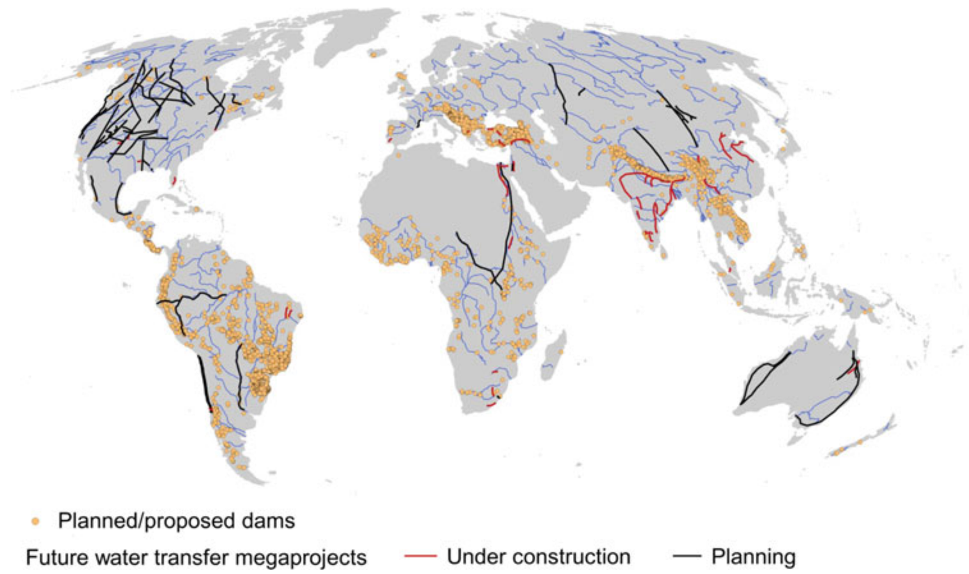

Fig. 16.1 Spatial location of global water transfer megaprojects, either under construction or in the planning phase (modified after Shumilova et al. 2019)

(−99% and −97%, respectively; He et al. 2019). Among taxonomic groups, mega-fishes exhibited the greatest global decline (−94%). Sturgeons, for example, survived 200 million years of global change—including cold and hot times; however, it took less than 150 years to bring them close to extinction. Today, 24 out of 26 sturgeon species worldwide are threatened with extinction or are already extinct in the wild. Furthermore, freshwater megafauna has experienced major range contractions. For example, distribution ranges of 42% of all freshwater megafauna species in Europe have contracted by more than 40% compared to historical areas. The main threats to freshwater megafauna include overexploitation, dam construction, habitat degradation, and pollution. Overall, 54% of the 155 megafauna species assessed are listed as threatened by the IUCN Red List (He et al. 2017, 2019; Fig. 1). A very recent example is the global extinction of the Chinese paddlefish, a charismatic mega-fish that was up to four metres long and lived in the Yangtze River (Zhang et al. 2020).

In China, 1,323 freshwater fish species are currently known. 877 species are endemic, and about 15% are listed as threatened (Xing et al. 2016) compared to 38 and 41% in Europe and North America, respectively (Kottelat and Freyhof 2007). However, the estimation of threatened species is a clear underestimation because the past decades have not been taken into account in the determination of the conservation status of China´s freshwater fish species.

Among the 1,280 freshwater crab species globally, more than one-quarter are threatened with extinction, only about one-third are not at risk, and the remainder lack sufficient evidence to assess their status (Cumberlidge et al. 2009). Indeed, the percentage of species at risk of extinction may only be greater for amphibians and aquatic reptiles.

In the European Union, according to the European Environmental Agency, only 10.5% of all rivers are in a very good ecological status (country range: 0.0–24%) and 31% are in a good ecological status (range: 0.8–66%; https://www.eea.europa.eu). The goal of the Water Framework Directive (WFD) is to reach a good ecological status for all rivers by the year 2027. However, there is no possibility of reaching this goal; indeed, in most countries, we are seeing no or only slight increases in the ecological status of rivers and streams. Moreover, a high proportion of ecologically valuable rivers and streams are not yet protected—and we may experience a further deterioration of many of these rivers despite the "no deterioration" principle of the WFD. A key reason for the deterioration of the ecological status of European rivers and streams is the ongoing boom in hydropower plant construction. Furthermore, the WFD is in competition with directives in the agriculture, energy, and infrastructure construction sectors. Hence, there is an urgent need to develop synergies among the different sectors, which would require a more systemic and holistic view of the challenges we are facing, and the solutions we must develop and implement.

Moran et al. (2018), for example, have proposed innovative solutions for hydropower: (i) environmental and social impact assessments (EIA, SIA) need to be carried out by firms and organizations serving citizens and not dam builders, (ii) functioning fish passage must be constructed and mimicking seasonal flow regime allowed, (iii) better governance must be established around dams, (iv) greater transparency about the true costs associated with dam construction are required, and (iv) innovative techniques which prohibit the construction of huge barriers must be developed and finally implemented.

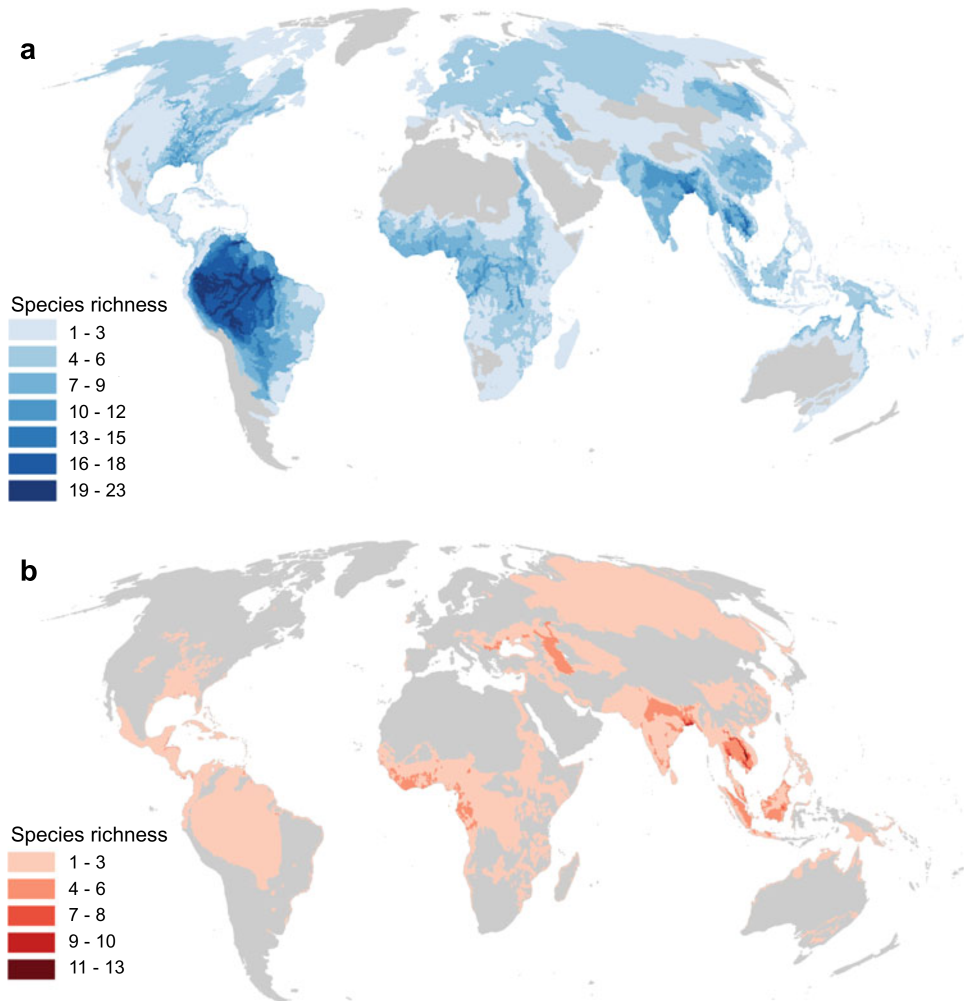

Fig. 16.2 **a** Global freshwater megafauna diversity and **b** number of threatened freshwater megafauna species (modified after He et al. 2019, unpublished)

Renewable energy is an important contribution in meeting growing energy demands and mitigating climate change. However, hydropower clearly has the greatest environmental effects of the main renewable energy sources (wind, solar, and hydropower), despite the fact that hydropower is booming in ecologically highly sensitive regions such as in the Amazon and Congo Basins, as well as in SE Asia, the Balkans, and in Anatolia (Gibson et al. 2017).

In Europe, we need to improve the coherence among the various environmental and sectorial EU policies and directives to prevent biodiversity loss and to support a wide range of ecosystem services. Synergies between the WFD and Nature Directives, as well as with other directives, must be developed. Ecosystem-based management presents us with a way forward; however, there is a risk of establishing yet another strategy without a clear political will of implementation. The current degradation of streams and rivers due to a boom in small hydropower plants and unsustainable agricultural development demonstrates the existing limitations of the WFD. Hermoso (2017), for example, has stated that weak legislation regulating hydropower project approval may cause irreversible damages to freshwater biodiversity and ecosystem services and, hence, freshwaters could become the biggest losers of the Paris Agreement.

16.7 An Engineered Water Future

Globally, freshwater is unevenly distributed, both in time and space. Climate change, land-use alteration, and increasing human exploitation will further increase the pressure on water as a resource for human welfare and on inland water ecosystems, thereby intensifying the uneven distribution of freshwater.

There is a growing belief that we may solve the increasing challenges in the water sector with major engineering solutions, including the construction of dams, water transfer projects, desalinization plants, or the like (e.g., Zarfl et al. 2015; Shumilova et al. 2019). However, many engineering projects, in particular so-called megaprojects, are often high-risk projects because they require major financial investments, demand long time frames from planning to completion, and may have major socio-economic and environmental ramifications. Concurrently, the social, economic, and environmental consequences of these projects do not receive adequate attention in the decision-making process. Furthermore, we need a systemic approach—due to path dependencies—and a transformative knowledge base to cope with the immense challenges humankind is facing.

We need global databases and maps, including temporal trends, of major water engineering projects (e.g., dam, water transfer, desalinization, restoration projects)—current, under construction, planned, and proposed (these data are either already available or must be complemented). These data must be linked with data on other pressures relevant for water systems (e.g., roads, artificial light, mining areas), and with data on biodiversity (e.g., freshwater megafauna) and ecosystem processes and services. We must ensure major engineering projects (megaprojects) are included in global and basin hydrological models. In addition, we need internationally agreed criteria to assess the ecological, social, and economic impacts of megaprojects, and the water-energy-food nexus must be extended to include further components such as mining and cultural diversity. Alternative solutions to mega-engineering projects, such as green infrastructure, linked natural and technical systems, local solutions, etc., must be considered, too (see Box 16.1). It is obvious that the discussion of alternative options will finally lead to better solutions. Overall, transdisciplinary research approaches are required, integrating academic and societal knowledge.

16.8 A Blueprint for Freshwater Life

Freshwater ecosystems must be put on the world map in terms of their conservation values, service values to humanity, and for their amazing diversity of life, which is so poorly understood and recognised today. The *Alliance of Freshwater Life* is a global initiative, uniting specialists in research, data synthesis, conservation, education and outreach, and policy making. This expert network aims to provide the critical mass required for the effective representation of freshwater biodiversity at policy meetings, to develop solutions balancing the needs of development and conservation, and to better convey the important role freshwater ecosystems play in human well-being (Darwall et al. 2018).

A blueprint of freshwater life will: (i) build greater global awareness of the values of freshwater ecosystems and their species; (ii) mobilise the huge body of existing research information, such as on the functioning of wetlands, for application to the sustainable management and conservation of the world's freshwater ecosystems; (iii) fill the extensive information gaps on freshwater ecosystems as needed to inform sustainable development; and (iv) bring forward the science of freshwater ecosystems to develop and inform conservation and development policy (Darwall et al. 2018). Indeed, we need to manage freshwater(s) as hybrid systems, i.e., as a resource for human use as well as highly valuable ecosystems. To do so, we need global databases and maps, including solid information on temporal trends, environmental drivers, human pressures, and biodiversity and ecosystem services. This will enable us to identify areas of high value and high risk and serve as a base for decision-making (e.g., Schmidt-Kloiber et al. 2019).

Species distribution data are crucial for improving our understanding of spatial and temporal changes in biodiversity (see detailed information: Schmidt-Kloiber et al. 2019). This is especially the case for freshwater systems, which are strongly affected by global change. Currently, freshwater biodiversity data are often difficult to access because systematic data publishing practices have not yet been adopted by the freshwater research community. The Freshwater Information Platform (FIP; www.freshwaterplatform.eu)—initiated through the EU-funded BioFresh project—aims at pooling freshwater-related research information from various projects and initiatives to make it accessible to scientists, water managers and conservationists, as well as the interested public. The FIP consists of several components, three of which are mentioned: (1) The Freshwater Biodiversity Data Portal aims at mobilising freshwater biodiversity data, making them available online. Datasets in the portal are described and documented in the (2) Freshwater Metadata base and published as open-access articles in the Freshwater Metadata Journal. The use of collected datasets for large-scale analyses and models is demonstrated in the (3) Global Freshwater Biodiversity Atlas that publishes interactive online maps featuring research results on freshwater biodiversity, resources, threats, and conservation priorities. Data and information are the basis for knowledge, and if publicly funded, these data must be made openly accessible, considering ethical issues and intellectual property rights (Schmidt-Kloiber et al. 2019).

Reid et al. (2019) advocate hybrid approaches that manage freshwaters as crucial ecosystems for human life support as well as essential hotspots of biodiversity and ecological function. Indeed, we need to manage freshwater(s) as hybrid systems, i.e., as a resource for human use as well as extremely valuable ecosystems. At the same time, we are not fully aware of the extent to which humans have and are planning to re-engineer the global hydrological network and flows through the construction of large dams, water transfer megaprojects, and other engineering projects. Indeed, we most likely are merely at the beginning of the "great acceleration" of the Anthropocene and therefore underestimate the environmental alterations we will face in the near future, in particular in the water sector.

Box 16.1: Three examples of large-scale restoration and management schemes

The **Four Major Rivers Restoration** project was the most important component of South Korea's national Green Growth Policy (e.g., Lah et al. 2015). At least US$ 19 billion was invested into this multi-purpose megaproject. Although it is too early to assess the overall achievements of the project, it has helped improve water quality, minimise water scarcity, reduce flooding risks, and stimulate local economies. However, it is more of an engineering project than a restoration project by building 16 dams, dredging 570 million m^3 of sand and gravel, and deepening nearly 700 km of riverbed. Indeed, the project was criticized by many scientists who accused the government of ignoring data and expert recommendations (e.g., Normile 2010).

The **Emscher River** (catchment area: 793 km^2) **restoration** is one of the largest water management projects in Europe, located in the densely populated "Ruhr Metropolitan Area" of the Federal State of North Rhine-Westphalia, Germany (for details, see Gerner et al. 2018). The project started in 1990, converting previously highly modified open wastewater channels with concrete beds into near natural river channels. An underground sewer network of more than 400 km has been constructed to separate waste and river water, and concrete river walls have been removed, piped rivers opened, stream profiles widened, and artificial wetlands created. The estimated costs of this project are approx. €5.3 billion.

The **Comprehensive Everglades Restoration Plan** (CERP) was approved in 2000. It consists of over 60 civil works projects that have been designed and implemented over a 30+ year period, with an estimated cost of more than US$ 10 billion. It seeks to correct an earlier attempt at water management in South Florida and improve water availability during the dry season and reduce flooding of urban and agricultural areas during the wet season (see Perry 2004; Sklar et al. 2005). The main aims are to restore, preserve, and protect the South Florida ecosystem while providing for other water-related needs of the region, including water supply and flood protection.

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Klement Tockner received a PhD in zoology and botany from the University of Vienna and a Titular Professorship at ETH Zurich. He is Director General of the Senckenberg Gesellschaft für Naturforschung and Professor for Ecosystem Sciences at Goethe Universität in Frankfurt, former president of the Austrian Science Fund (FWF), professor for Aquatic Ecology at the Free University Berlin, and former director of the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin. He is member of several international scientific committees and advisory boards, and elected member of the German National Academy of Sciences, Leopoldina, and the Austrian Academy of Sciences.