nature geoscience

REVIEW ARTICLE
https://doi.org/10.1038/s41561-018-0262-x

Anthropogenic stresses on the world's big rivers

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The world's big rivers and their floodplains were central to development of civilization and are now home to *c*. 2.7 billion people. They are economically vital whilst also constituting some of the most diverse habitats on Earth. However, a number of anthropogenic stressors, including large-scale damming, hydrological change, pollution, introduction of non-native species and sediment mining, challenge their integrity and future, as never before. The rapidity and extent of such change is so great that large-scale, and potentially irreparable, transformations may ensue in periods of years to decades, with ecosystem collapse being possible in some big rivers. Prioritizing the fate of the world's great river corridors on an international political stage is imperative. Future sustainable management, and establishment of environmental flow requirements for the world's big rivers, must be supported through co-ordinated international funding, and trans-continental political agreement to monitor these rivers, finance their continual upkeep and help ameliorate increasing anthropogenic pressures. To have any effect, all of these must be set within an inclusive governance framework across scales, organizations and local populace.

The world's great rivers have been foci for the origin and growth of human culture[1–5], support huge populations[6] (Fig. 1; Supplementary Table 1) and constitute some of the most diverse ecosystems on the surface of the globe[7,8]. These big rivers (Fig. 1, see definition; Supplementary Information) are largely transboundary[9,10], and can help promote both regional collaborations and conflicts[11–17]. Standing on the riverbanks at the mouth of a big river gives a sense of spatial connections — in the water, sediment, ecology and cultures that the river unites — as well as temporal corridors into the evolution of the landscape, linked ecosystems and human civilization. The world's big rivers hold huge societal importance in the benefits they bring through food production, hydropower generation and providing trade routes. For instance, hydropower provides 16% of the world's total electricity and 70% of renewable electricity[18]. In addition, the annual use of freshwater from surface and ground waters of the world's artificial reservoirs, for the purposes of hydropower generation, irrigation, industrial and domestic water supply, flood protection, fishing and recreation, is valued at US$265 × 10^9 per year[19]. The economic importance of big rivers is shown by evaluation of economic dependence and risk for transboundary rivers[9] as a function of urban and agricultural (irrigation) activity (Supplementary Table 1). Such analysis shows that 15 (Congo, Nile, La Plata, Niger, Volga, Zambezi, Ganges-Brahmaputra, Orinoco, Tigris, Indus, Danube, Mekong, Ganges, Irrawaddy and Rhine) of the 24 transboundary river basins considered herein have a very high or high economic dependence on these waterways, with the Amazon and Mississippi rivers possessing a moderate dependence[9]. However, population growth, and the rising demand for water, power, food and land, have generated increasing stresses on the world's great waterways[9,17], and we have reached a time when the integrity of many of the world's largest rivers is being irrevocably threatened by a combination of anthropogenic stressors[20–23]. At the downstream termination of many big rivers, the world's great deltas are home to 500 million people[1,24], but are threatened by relative sea-level rise, due to a combination of rising sea level, land subsidence through groundwater abstraction and upstream water and sediment starvation[1,24].

The large-scale controls on the location, morphology and ecosystems of big rivers centre around their plate tectonic setting and relationship to topographic gradients, geology, controlling climatic factors and the influence of relative sea level[25,26]. Some researchers have proposed that big rivers possess distinctly different characteristics from smaller channels[27], and perhaps adopt an anabranching channel pattern that is the end-member adjustment for large fluvial systems[28]. Such large channels also display considerable complexity in their planform and floodplain-channel connectivity[29]. The morphology of, and sediment flux from, the world's great rivers have changed radically over periods of thousands to millions of years, with the sea-level minimum at the Last Glacial Maximum having extended channel networks, especially in Southeast Asia[30]. Such long-term changes have also had an indelible imprint on biological evolution, creating a direct link between species differentiation and large river basin development[31–33]. On a shorter timescale, river channel migration has been shown to be responsive to the imposed water discharge and sediment flux[34]. For example, the 1950 Assam earthquake introduced *c*. 45 × 10^9 m^3 of sediment into the Jamuna–Padma–Meghna river system[35]. This sediment pulse has been argued to have created a wave of bed-load material, with a celerity between 16 and 32 km yr^{-1}, which caused channel widening, and associated societal and engineering pressures, over the succeeding 50 years[35]. However, anthropogenic change is enforcing more rapid, and more long-lasting, radical changes on the world's great freshwater corridors. This paper provides a review of aspects of the world's big rivers (see Fig. 1 and Supplementary Table 1 for details of the world's 32 largest rivers) and details the principal anthropogenic stressors. This synthesis reveals that unless concerted and truly multidisciplinary and intergovernmental efforts are forwarded rapidly, several of these river basins will suffer immense change within decades and from which there will be no recovery.

Damming

The last two decades have witnessed a resurgence in the plans for, and construction of, new hydroelectric power schemes and 'megadams'[36–38] (Fig. 1; Supplementary Table 1; megadams are those with a height >15 m (ref. [37]); dams depicted in Fig. 1 have a maximum design capacity of 1 MW or greater[38]), with the worldwide installed GW hydropower capacity having increased 55% from 2000 to 2015 (ref. [39]). Such growth has been fostered by energy demands to

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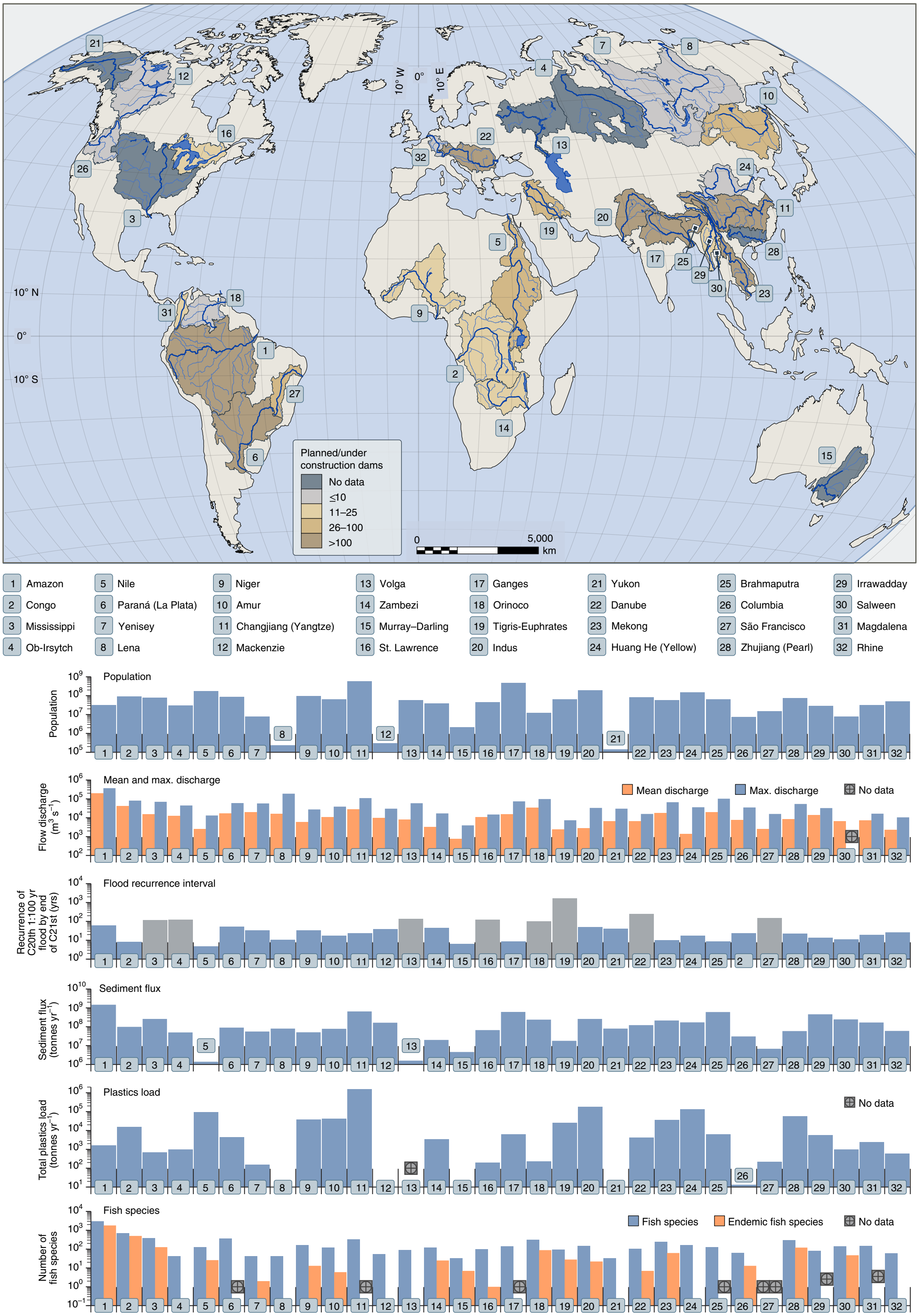
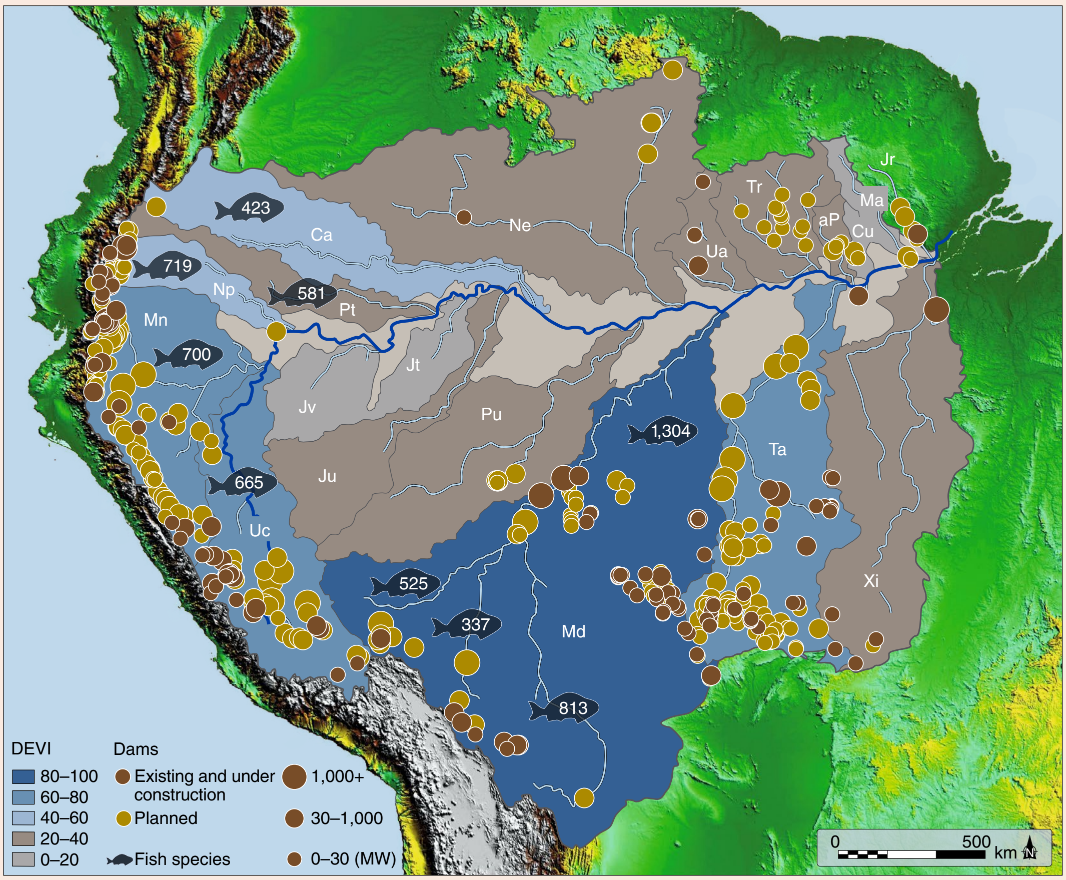


Fig. 1 | Map of the world's 32 largest rivers, listed in order of drainage basin area, and their principal tributaries. The colour shading for each river basin shows the number of planned or under construction dams[38]. Histograms display summary data for human population, mean annual and historic maximum water discharge, predicted recurrence of the twentieth century 1:100-year flood by the end of twenty-first century (values >100 years shaded in grey), mean annual sediment flux and plastics load, and the total number of fish and endemic fish species for each river basin. Map projection is Winkel tripel. Data and data sources, together with additional data on these rivers (refs. [243–263]), are given in Supplementary Table 1. 'Big' is defined herein as those rivers with a basin area greater than 0.164 million km^2, a mean annual water discharge in excess of 2,400 $m^3 s^{-1}$ (except for the Murray–Darling River) and a length greater than 1,400 km.

Box 1 | The Amazon River: just dammed or doomed?

In the world's largest river basin, recent work[235] has stressed the enormous potential impact of damming, and highlighted how individual tributary basins must be assessed to reveal the full impact of hydropower construction. The potential effects of damming may be felt in reductions in downstream sediment and nutrient supply, changes to the annual flood pulse and fish yields, reservoir siltation, the emission of greenhouse gases and mercury contamination[236]. Latrubesse et al.[235] advocate use of a Dam Environmental Vulnerability Index (DEVI) as a method for assessing the likely impacts of damming, which combines measures of basin integrity due to land use changes, fluvial dynamics driven by sediment transport changes, and impacts due to dam construction. These results highlight the extreme fragility of the Amazon Basin, and especially the Madeira, Tapajos, Ucayali and Maranon sub-basins that face immense potential changes. This work[235] stresses how an integrated management approach, involving governmental agencies, the power sector, scientific research and the user community, is a prerequisite to foster a sustainable future for this most diverse riverine ecosystem.



DEVI[235] for sub-basins within the Amazon basin, with higher DEVI values indicating a greater risk. Dots indicate location and MW size of existing and proposed dams. Andean foreland rivers: Mn, Marañon; Uc, Ucayali; Np, Napo; Pt, Putumayo; Ca, Caqueta-Japura. Cratonic rivers: Jr, Jari; Pa, Paru; Cu, Curuapenema; Ma, Maricurua; Ta, Tapajós; Xi, Xingu (see Supplemetary Fig. 2 for images illustrating the effects of construction of the Belo Monte Dam); Tr, Trombetas; Ne, Negro; Ua, Uatumã. Mixed-terrain river: Md, Madeira. Lowland rivers: Ju, Juruá; Pu, Purús; Jt, Jutaí; Jv, Javari. Number of fish species in Amazon sub-basins taken from ref. [237].

support population and sustain industrial and urban growth, and a contention that as a power source hydropower may reduce carbon emissions. At present, only *c*. 22% of the world's technically feasible hydropower is being harnessed[38]. Large dams may also be multipurpose, and not exclusively for energy generation, with uses in irrigation, flood control and provision of drinking water[38,39].

Construction of megadams, located largely on the world's big rivers[38] (Fig. 1; Supplementary Table 1), also poses considerable risks, such as ecosystem fragmentation[39,40] (see section 'Fragmentation'), habitat changes, hydrologic alteration of the quantity and timing of river flow, downstream sediment starvation[39–41], downstream changes in water and food security[42,43], relocation of animal and human populations, species extinctions[44] and release of greenhouse gases from decaying vegetation[36,45–47]. Existing and potential damming of the Amazon (Box 1, see figure) and Mekong (Supplementary Fig. 1) rivers provides an indication of such large-scale environmental threats.

The hydrological, morphological and ecological impact of large dams can be dramatic, as exemplified by the Huang He (Yellow) River, China — a river that pre-impoundment had the highest total sediment flux of any river on Earth (Fig. 2; Supplementary Table 1). Such 'hyperconcentrations' of fine sediment were probably a product

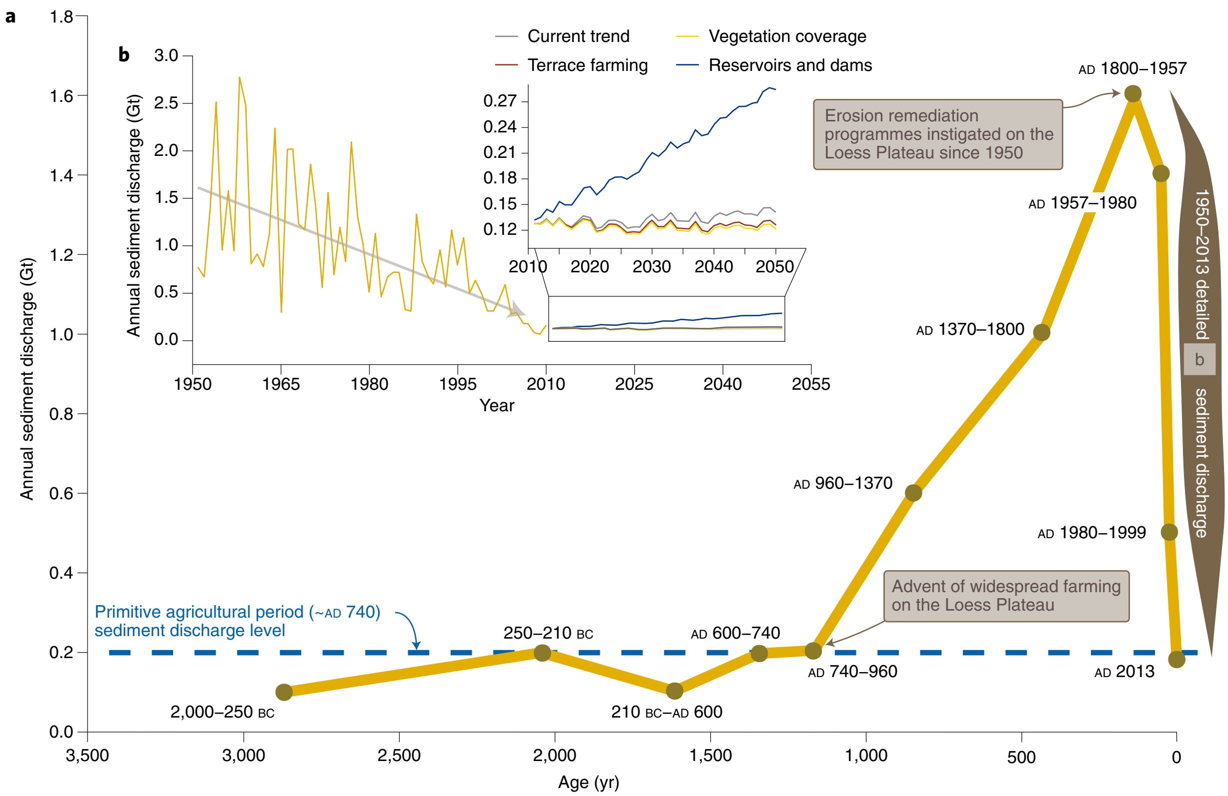


Fig. 2 | Sediment yield from the Huang He (Yellow) River. a, Sediment yield over the past 3,500 years[50]. **b**, Detail for time period since 1950, with future sediment yield predicted assuming a trend of increasing vegetation coverage and terrace farming, but a decrease in efficiency of check dams and reservoirs, resulting in a slight increase in sediment discharge[54]. Current trend refers to sediment yield without considering these factors.

of deforestation and agricultural development of the Loess Plateau in AD 960–1950 (refs. [48,49]) (Fig. 2), with sediment yield before *c.* AD 740 being *c.* 13% of its peak value of 1.6 Gt year^{-1} in *c.* 1950 (refs. [50,51]). However, construction of small check dams[52] and large dams[53–55], and especially the Xiaolangdi Reservoir[53] that became operational in the early 2000s, together with China's 'Grain for Green' project that has revegetated the Loess Plateau[50], have resulted in greatly diminished flow and sediment reaching the delta[53–55]. These interventions have reduced sediment deposition in the lower Huang He River from an average of 111 × 10^6 m^3 yr^{-1} over the period 1951–2000, to a state where the channel suffered net erosion of up to 361 × 10^6 m^3 yr^{-1} in 2002–2003 (ref. [53]). This decreased sediment load caused concomitant changes to both river-bed elevations[53], which have reduced the likelihood of flooding from the 'perched' channels[49] of the Huang He River, and the advance and retreat of sediment lobes on the delta[56,57]. Operation of a water–sediment regulation scheme (WSRS) has ameliorated sediment trapping in the Xiaolangdi Reservoir and downstream sediment starvation to some extent[53,58], although sediment flushing in a yearly flow and sediment release has been shown to create conditions that can cause up to 20% fish mortality[53]. This mirrors research that has shown increased fish mortality due to increases in fine sediment concentration[59,60]. Current estimates[54] indicate the sediment yield of the Huang He River will likely increase slightly (Fig. 2b) due to decreasing efficiency of upstream sediment trapping, and suggests vegetation restoration and management in the Loess Plateau will play the major role in catchment planning. The Huang He River thus presents a compelling story of a big river that has undergone first increases in sediment flux due to changes in catchment land use, and then dramatic decreases due to water and soil conservation practises in the Loess Plateau, damming and water abstraction.

Apart from the environmental, ecological and societal stresses created by large dams, their economic justification has been challenged recently[61]. Cost overruns in construction are present in all regions of the world, and are apparent in 75% of large dams, with average costs being 96% higher than estimated costs[61]. Vigorous debate continues on the issue of cost overruns, with other analyses arguing that whilst cost and time overruns are part of large dam construction worldwide, their eventual benefits still yield a net positive[62]. Modulation of extreme flood levels due to dam impoundment may avert excessive downstream flooding, although recent analysis of the Changjiang River[63] demonstrates that morphological changes and floodplain loss due to bank erosion may lessen these flood buffering capabilities. Disparate views also remain on the basic questions that need to be asked when considering new hydropower schemes, ranging from ways to optimize the required dam portfolio to meet energy and fisheries requirements whilst securing a maximal biodiversity[42], to whether dams are needed or not[64,65], and fuller consideration of the social impacts[66,67] and cultural[68] costs that are rarely, if ever, considered in such projects. A picture emerges that the energy economics and environmental impacts of large dams often need to be evaluated more fully, and in a holistic manner, in comparison to other renewable energy sources, and placed within the context of energy demands and sovereign energy, water and food security.

It is also inevitable that reservoirs and dams will eventually require decommissioning. Although the removal of relatively small dams is proceeding in both the United States (US) and Europe, with over 1,200 being completed to date in the US[69], the decommissioning of large dams is an issue that still has to be tackled[70,71], especially in developing countries[72]. Whilst sediment flushing will extend the lifetime of a reservoir, assessment of the condition of aging dams and plans for their removal must adopt an integrative approach that considers all the stressors on the ecosystem[70], and calls for long-lived consistent monitoring[71,72] and early planning, rather than efforts consigned as an afterthought. Some studies have indicated that

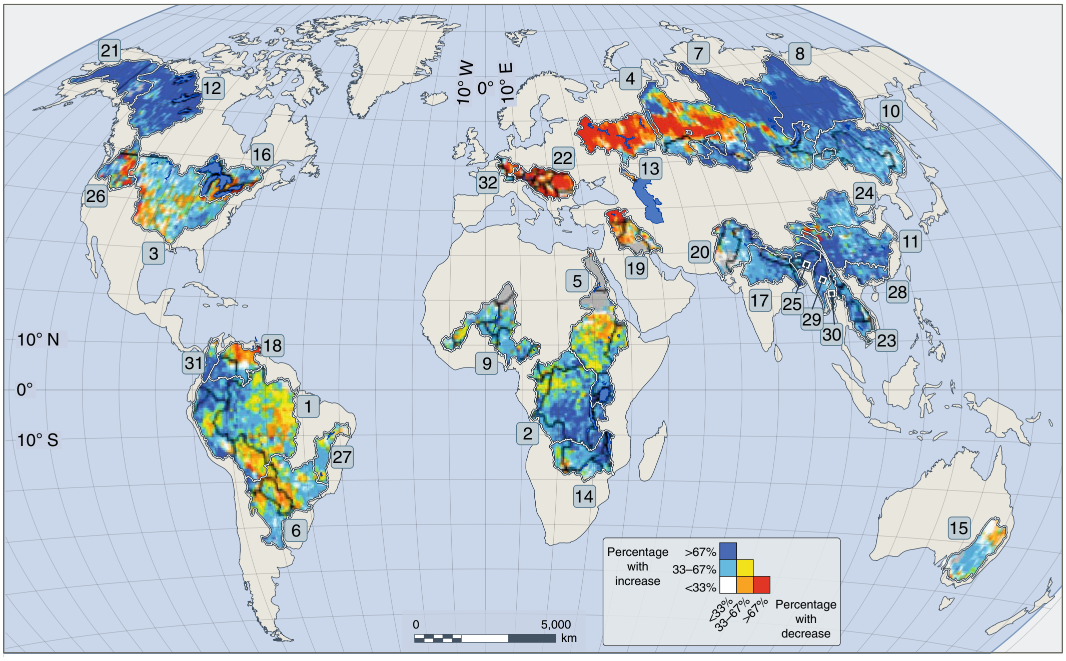


Fig. 3 | Consistency (percentage of all models) in the magnitude of estimated 100-year recurrence interval floods in 2050 from 21 climate models[75], showing regions of increased (blue) and decreased (red) flow. Grey shaded areas are those with annual runoff <10 mm year^{-1}. Numbers refer to river basins listed in Fig. 1.

the storage capacity of large reservoirs may have already reached a peak[73], due to sedimentation in reservoirs and increased demand for water. All these considerations may now leave the hydropower policies of large countries, such as China, at a crossroads between construction and removal[71].

In face of the enormous, and potentially catastrophic, changes that may ensue following megadam construction, it is evident that the data by which we can assess such change are woefully insufficient[39,74]. It is startling that in an era of big data and big science, we possess so little data concerning the flux of sediment, nutrients and water through the world's big rivers, and which are plainly essential to guide decisions on managing hydrological, geomorphological, ecological and engineering change, and which must be set within a sustainable governance framework.

Climate change and flooding

Changes to the volume and timing of water delivery to some of the world's big rivers is likely to change under a warming climate[75–77], with concomitant effects on sediment flux and ecological functioning. Recent modelling of climate change and its potential effects on global flood risk[21,75] shows that the response is complex and relies on the context of individual river basins, rather than being simply a function of changing precipitation. Intensification of the hydrological cycle as a result of warmer air temperature is linked to more extreme rainfall over much of the world, particularly over short durations[78]. Comparison of results using a suite of climate change models[75] (Fig. 3) shows consistent increases in the magnitude and return periods of floods with a magnitude of the present-day 100-year flood in the Congo, Zambezi, Niger, Upper Amazon, Yenisey, Lena, Amur, Mackenzie and Yukon rivers, as well as most of the great rivers of Southeast Asia. Conversely, decreases in flood magnitude and return period are likely in the lower Nile, Tigris–Euphrates, Danube, Volga and Ob rivers and parts of the Mississippi basin (Fig. 3). Although such model results possess uncertainties, they indicate that under some climate scenarios, the current 100-year flood would occur twice as often across 40% of the world and over 60% of Southeast Asia, Central Africa, Central Europe and Canada[75]. Projections of global flood inundation[79] also indicate that the return period of a flood equivalent in size to the twentieth century 100-year flood will change by the late twenty-first century (2071–2100). These projections (Fig. 1) indicate that this size of flood would be experienced more frequently in 25 of the 32 river basins considered herein, with the Brahmaputra, Congo, Ganges, Lena, Mekong, Murray–Darling and Nile undergoing floods of this magnitude with a return period of *c.* 10 years. Importantly, a central point that emerges is that a greater proportion of the world's flood-prone population will probably see increases in flood frequency, with these findings also borne out by other models[80,81]. When linked to data concerning population and gross domestic product (GDP), recent estimates[78] indicate that under a 1.5 °C warming, approximately three-quarters of the world's population and GDP will probably experience increased exposure to flooding when compared to a 1976–2005 baseline, at an average of 100% increase in the population affected and 120% increase in cost of damage. The drivers of future global flood risk are both climate change and socio-economic growth, with global absolute flood damage perhaps increasing by up to a factor of 20 by the end of the century without action being taken, and with increases in flood risk being particularly severe in Southeast Asia[77]. In addition to flood magnitude and frequency, recent analysis of European flooding[82,83] suggests that the timing of flooding is changing in response to a changing climate, with differential responses across the continent due to differences in snowmelt timing, soil moisture maxima, changes to the North Atlantic Oscillation and increasing winter flows from the Atlantic. All these studies make it clear that our assumption of stationarity, which has underlain the management of flood risk, water supply and water quality, is no longer applicable[84,85]. This suggests that all decisions regarding large river water resources must be viewed through the lens of a changing climate and hydrological regime, and development of non-stationary probabilistic models[84].

The complexity of such feedbacks between climate and river flow are perhaps exemplified in considerations of the great rivers that flow from the mountains of Asia — the 'water tower' of Asia — that supply water, food and energy to some 3 billion people[86]. These rivers rely on both monsoonal rainfall and snowmelt[87], with snowmelt forming a larger percentage of total annual discharge in catchments in the west of the region, such as the Indus River in which snowmelt forms over 50% of the flow[87]. Future climate change may lead to opposing trends in water supplied by snowmelt and monsoon sources[6,86]. Reducing glacier size may lead to diminished flows in some rivers, especially low flows, with the Indus and Brahmaputra being at potentially severe risk of reduced flows by the mid-twenty-first century due to their large populations and high reliance on irrigation and meltwater[6]. However, for rivers where meltwater is a smaller percentage of the total flow, such as the Huang He River, increased precipitation from monsoonal rainfall may enhance water availability[6]. These changing trends in water supply have differing societal significance relating to irrigation, waste/pollutant disposal (low flow) and increased flooding.

The difficulty of predicting the effects of a changing climate on river flow is illustrated by the Mekong River, whose water and sediment flux is generated by both monsoon-related flow and tropical cyclones[88]. Some 14–29% of water and 32% of the suspended sediment load have been linked to the impact of tropical cyclones that track across the South China Sea and impact the Southeast Asian peninsula[88]. Sixty-three per cent of the decline in suspended sediment load over the period 1981–2005 at Kratie, Cambodia (from *c*. 53 to 32 Mt year^{-1}), can be attributed to the eastward shift in the tracks of tropical cyclones[88], which are projected to increase in frequency and intensity but move eastwards under a warming climate[89]. As the Mekong basin is already under severe pressure due to damming (Supplementary Fig. 1) and sediment mining (see section 'Sediment dredging, mining and bank erosion'), such climatic shifts may serve to further lessen the future delivery of sediment to the Mekong Delta. This has concomitant implications for food security and agricultural production[90,91], as well as the ecosystem services of vital habitats such as the Tonlé Sap Lake that supplies 80% of the protein for millions of people in Cambodia and beyond[92].

The influence of shorter-term climatic fluctuations, such as the El Niño Southern Oscillation (ENSO), have also been shown to be important in the hydrology of many large rivers[93], and the frequency of extreme ENSO events may increase under a warming climate[94]. Such shorter-term fluctuations may also have a local influence on hydropower generation[95]. The role of atmospheric rivers[96], which are narrow ribbons of large moisture flux from the sub-tropics to mid-latitudes, has also been linked to periods of both extreme drought and extreme precipitation in some areas of the globe[97–99]. Modelling results[99] (Supplementary Table 1) suggest that in some large river basins, atmospheric rivers may be highly influential in their contribution to high flows (>30% for the Amur, Zhujiang (Pearl), Columbia, St Lawrence, Volga, São Francisco, Murray–Darling and Tigris–Euphrates rivers) but far less significant in others (<5% for the Amazon, Congo, Orinoco, Magdalena and Nile rivers). The absence of atmospheric rivers can also significantly influence periods of low flow and drought (Supplementary Table 1), with their contribution to low flows being >50% in the Amur, Zhujiang, Columbia, Murray–Darling and Tigris–Euphrates river basins. Consequently, *c*. 300 million people are prone to floods or droughts due to the occurrence of atmospheric rivers[99].

Global warming has also been linked to potentially significant increases in the flow of Russia's three great Artic rivers — the Ob, Yenisey and Lena[100–102]. These rivers have a flood hydrograph dominated by snow melt and ice melt, with ice breakup occurring first in the south of these northerly flowing channels. Under a warmer climate, increased melting of ice and permafrost, with greater contributions from groundwater to river flow[101], are likely to alter both the timing and magnitude of flooding, together with a greater northward transport of moisture[102]. In these Russian rivers, such changes in flow discharge and timing, sediment transport capacity and increased vegetation growth aided by permafrost thawing, could induce changes in the planform channel morphology, potentially triggering the transformation of single to multi-thread channels and changes in planform channel stability[103].

A fundamental characteristic of large river corridors is the presence of extensive and complex floodplains[104–106], which serve key functions in terms of sediment/organic matter sequestration, ecosystem functioning and sustainable river management[107–112]. Changes to large river hydrology, whether caused by climate change, damming or water withdrawal/diversion (see section 'Water withdrawal/transfers'), may thus produce spatially and temporally complex changes to river-floodplain connectivity and the overbank delivery of water and sediment. As such connections are vital to the ecosystem services provided by aquatic and terrestrial taxa[111,113], future assessment and modelling of river channel change must integrally assess channel–floodplain interactions, their geomorphology and wetland ecology.

Pollution

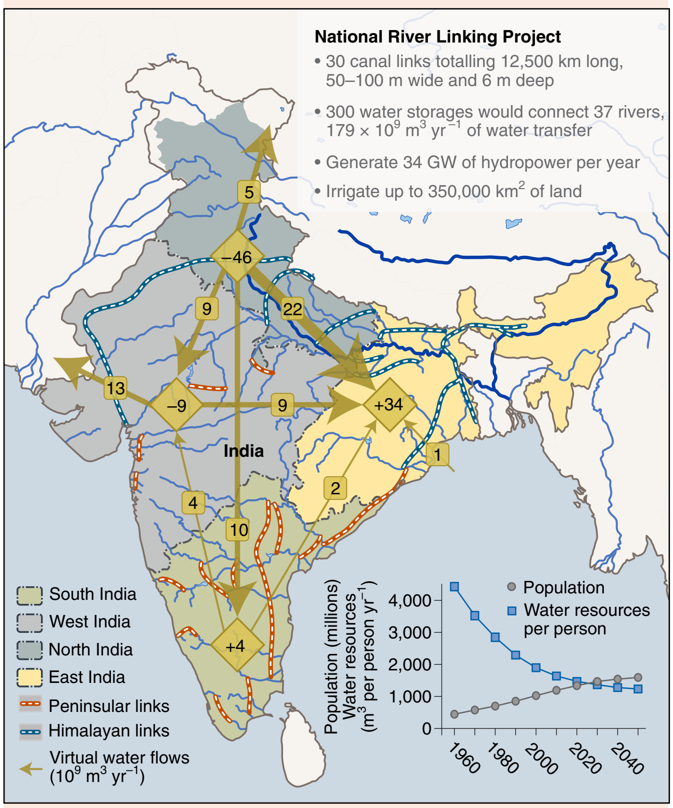
Rivers have long been used to dispose of waste of many types, away from regions of population, agriculture and industry. Although rivers such as the Danube have achieved significant reductions in pollution and an increase in water quality over the past 20 years[114,115], other large rivers in regions of dense population are under severe stress. In a recent assessment of global rivers[9], two principal categories of pollutant within rivers were considered — nutrients (mainly nitrogen and phosphorous) that can lead to enrichment, algal blooms and eutrophication, and pathogens (largely human waste). Astonishingly, this analysis (Supplementary Fig. 3) suggests that water quality in over 80% of the world's transboundary rivers, including many big rivers, is severely affected by: (1) nutrient over-enrichment, such as in the Mississippi, Danube, Rhine and Indus rivers; or (2) wastewater pathogens, such as in the Amazon, Ganges/Brahmaputra, Paraná, Nile, Congo, Yenisey, Niger, Zambezi, Lena, Amur, Indus, Irrawaddy, Salween and Mekong rivers.

The magnitude of the issue of pollution in developing countries is illustrated by the Ganges River that sustains 43% of India's population[116], but has long suffered significant problems with untreated faecal waste, pesticides and heavy metal pollution[117–121] that have resulted in the failure of several pollution control projects[116]. Reducing the influx of waste into the Ganges is not only a physical problem that concerns legislation, flow volumes, investment and implementation, but also one intrinsically linked to the religious, social and cultural place of the Ganges[122]. Such issues are brought into focus by mass ritualistic bathing[123], and events such as the Kumbh Mela, a Hindu religious festival that is the world's largest mass gathering, which in 2013 attracted 120 million people over a period of 55 days to the confluence of the Ganges and Yamuna rivers[124]. Such events both supply large quantities of faecal material to the river, which increases levels of ammonia, biochemical oxygen demand and coliform bacteria, and increases turbidity levels due to bathing[123], as well as exposing bathers to the already polluted water of the Ganges.

Besides the physical, chemical and organic pollution outlined above, two other sources of pollution are worthy of note. First, recent research is uncovering the presence, extent and likely significance of macro- and micro- plastic pollution within many freshwater bodies[125–131]. The quantity of plastics supplied to a river shows a strong correlation with population density, urbanization and degree of wastewater treatment[126,127,129,132], although sewage sludge[128], which may contain synthetic fibres and microplastics from personal care or household products, may provide a significant source of plastics pollution that can make its way into rivers from agricultural regions. Recent modelling reveals that between 1.15–2.41 (ref. [132]) or 0.41–4.0 (ref. [129]) million tonnes of plastic waste enters the world's oceans from rivers annually (Fig. 1; Supplementary Table 1). Seventy-four per cent of this waste is delivered between May and October[132], and

Box 2 | Engineering new rivers

The government of India has embarked on construction of a network of canals under the National River Linking Project (NRLP), which is designed to transfer water from regions of surplus to areas of deficit, at a cost of US$120 billion (refs. [238,239]). The NRLP has two components[141] — for the peninsular and Himalayan rivers of India — that aim to provide water, food, power and flood protection[239] to India's large and burgeoning population, which may reach 1.5 billion by 2050 (ref. [239]). Water-stressed countries are defined by a per capita water availability of less than 1,700 $m^3\ yr^{-1}$: for India, this figure is currently 1,410 $m^3\ yr^{-1}$ but is predicted to fall by *c.* 18% to 1,154 $m^3\ yr^{-1}$ (ref. [240]) by 2060, thus demanding changes to water supply and/or use of water resources. However, the NRLP has raised a swath of concerns[144,148], including the spread of pollution within the channel network, alterations to the flow regime, introduction and spread of non-native species, a loss in fish biodiversity[241], impediment to fish migration by dams and salinization, displacement of *c.* 5.5 million people[141] and starvation of sediment supply to downstream deltas[242]. In addition, estimates show that the movement of virtual water (the water used to create goods and services) in India[239] ($106 \times 10^9\ m^3\ yr^{-1}$) is essentially the same as that proposed by the NRLP ($107 \times 10^9\ m^3\ yr^{-1}$), but in the opposite direction from water-scarce to water-rich regions. This trade exacerbates water scarcity[239] and suggests that a more holistic approach to water security must involve alternative strategies for water, such as the role of aquifer storage, and improved efficiency of agricultural and urban water use (for instance, up to 40% of Delhi's water is lost through leaky pipes[139]).



Interlinking of Indian rivers in the NRLP. Shown is: (1) the principal rivers and proposed diversion canals[139] (base map from: https://d-maps.com/pays.php?num_pay=84&lang=en); (2) virtual water flows between four regions in India with loss or gain of virtual water shown in diamonds, and virtual water transfers between regions shown by arrows and square boxes[239]; and (3) predicted population growth and per capita water resources until 2050 (ref. [141]).

is dominated by contributions from large Chinese rivers during the monsoon season[132], with 86% of the global plastic waste being contributed from Asian rivers[132]. This dominance of plastic waste output from a few large rivers is highlighted in estimates that indicate that the Changjiang, Indus and Huang He rivers may transport 63%, 7% and 5%, respectively, of the world's plastic waste delivered to the oceans[129]. Although the volumes in these estimates are probably conservative, they indicate the scale of the problem, but also suggest that management of plastics emissions from relatively few river sources could impact greatly on the quantity of plastic delivered to the world's oceans[132].

Secondly, increasing urbanization and changing global climates are raising the temperature of many rivers[133,134]. The sensitivity of aquatic species to raised water temperatures is well known[135], with thermal habitat often being species specific, and increased water temperature may potentially lead to the extinction of some species, or changes in species distributions[135]. In regions that may experience strong increases in water temperature and decreases in river flow, such as eastern China, an economic impact may be evidenced in effects on thermoelectric power generation and drinking water production[134].

Water withdrawal/transfers

In regions of the world where water demand far exceeds water supply, large-scale inter- and intra-basin water transfers and diversions have a long history of planning and construction[136,137], including those in China[138], India[139–144] and Brazil[145]. Such schemes aim largely to aid irrigation, help control flooding, increase food production, improve sanitation, assist disease control and generate power[141].

The potential impact of such water diversions is shown by the Farakka[146] and Teesta[147] barrages in India and Bangladesh. The Farakka barrage, located on the Ganges River 17 km upstream from the Bangladesh border, was completed in 1975 and designed to direct more water down the Hooghly River to Kolkata at low flow. However, this has had deleterious effects on downstream Bangladesh, including destruction of breeding grounds for 109 aquatic Gangetic species, intrusion of saline water in coastal southwest Bangladesh and a concomitant reduction in fish and agricultural diversity[146,148]. More recently, the Teesta River barrage, although designed to provide irrigation water in parts of Bangladesh, has caused severe water shortages downstream, and its benefits for irrigation and food security have been questioned[147,149]. Inter-basin water transfer (Box 2, figure; Supplementary Fig. 4) seemingly offers a quick but often very expensive fix, including river fragmentation, alterations to flow regimes, introduction of non-native species, salinization and unplanned urban and irrigation development[137]. Such large-scale inter-basin transfer schemes also call into question whether the river basin is then the appropriate unit to consider for integrated water management[150]. In addition, the human consumption of water has been shown to intensify the magnitude and frequency of drought[151] through substantially reducing local and downstream flow, especially during low-flow conditions. This is due principally to irrigation, although domestic and industrial use contribute to hydrological drought intensification in the eastern US and Central Europe[151]. The presence of large-scale dams in a river basin may help buffer such reduced flows, but human water consumption has been estimated to increase the frequency of droughts by 35%, 25% and 20% in Asia, North America and Europe, respectively[151].

Non-native species

The introduction of non-native species has produced ecological changes to many big rivers. A range of organisms has spread widely through freshwater ecosystems, with molluscs and fishes — such as zebra and quagga mussels[152] and Asian carp[153] — being some of the most dramatic examples. The macroinvertebrate population of the River Rhine, for example, has been severely altered by the spread

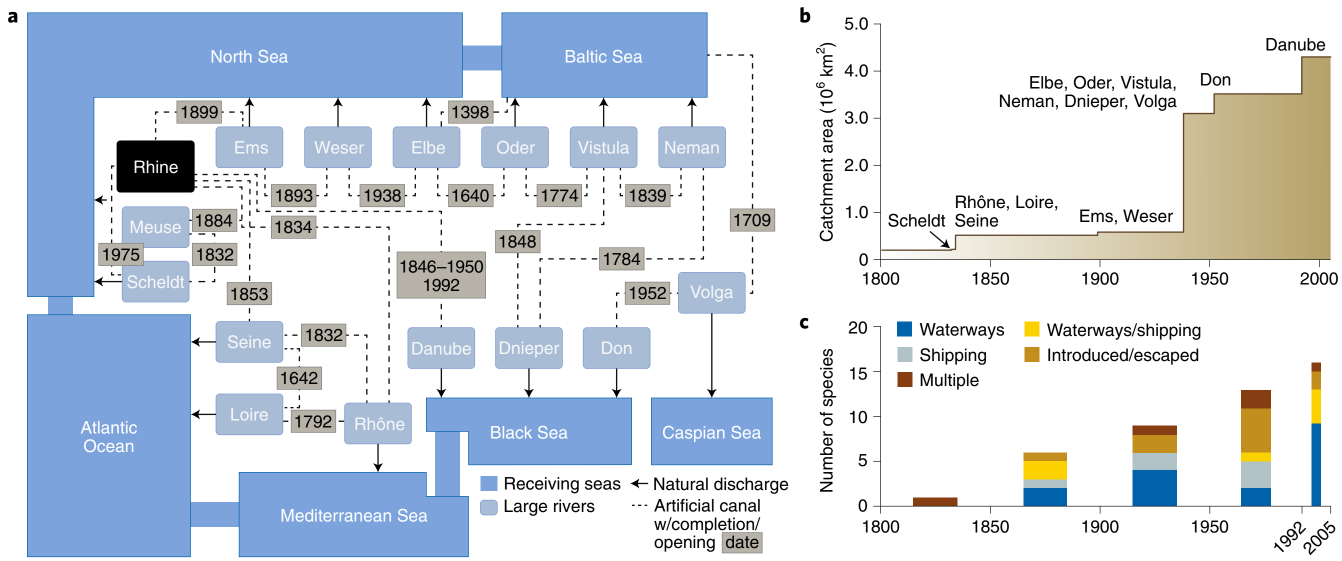


Fig. 4 | The spread of non-native species within the River Rhine and other rivers in Europe[155]. **a**, History of connections between the River Rhine and other large rivers via canals and sea routes. Grey boxes, large rivers; blue boxes, receiving seas; continuous lines, natural discharge; dotted lines, main artificial canal systems, with dates of completion or opening of canals. **b**,**c**, Temporal trends in catchment area (**b**), and the number of non-native species coded according to their dispersal vector (**c**). Dates of connection of main rivers are also indicated in **b.**

of non-native species that have become numerically dominant, as well as forcing a disappearance, or reduction, in the population of endemic species[154]. In 2009, it was estimated that over 11% of the macroinvertebrate species within the River Rhine comprised non-native species (dominantly crustaceans (51%), molluscs (22%) and annelid worms (11%)), and that these exotic species were more abundant in both the deltaic Rhine area, due to seaport connections, as well as the upper Rhine through the Rhine–Main–Danube canal. Analysis of the history of river connections and increasing potential source areas for non-native species (Fig. 4) reveals a strong control through increasing connectivity[155], providing a salutary lesson for river interlinking schemes. In addition, the spread of non-native species may show spatial variation, with species arriving at the upstream parts of the Rhine basin spreading more rapidly than those introduced from the mouth[155]. However, the time lag from upstream arrival to appearance at the delta was a maximum of 50 years, with seven species achieving this spread in one year[155], probably due to ships forming a rapid transport vector.

The Mississippi River drainage basin has also undergone rapid ecological change due to the spread of Asian Carp, which has resulted in massive ecosystem change, and significant financial investment to address the issue[153]. The problem is so acute that perhaps 80% of the biomass of some Mississippi tributaries is accounted for by this species, with engineering solutions involving electric fish barriers, underwater water cannons, targeted poisons and even potential redesign of the surface water system for Chicago[153] to attempt to stop the spread of Asian carp into the Great Lakes. However, halting the spread of such carp is not an easy matter and considerable ongoing research is being devoted to address this issue[156,157].

However, besides these examples, the introduction of other non-native species, such as aquatic vegetation and omnivorous decapods, has been widespread, and the role of non-native diseases, such as amphibian chytridiomycosis, Asian tapeworm and crayfish plague, points to an underappreciated and underestimated threat[152]. It is also apparent that the changing, and non-linear, effects of non-native species with other multiple stressors may create conditions that are easier, or harder, for further exotic species to inhabit, or jointly determine the ecosystem services that are available in a habitat[152]. This may make the effects of such non-native species even more difficult to manage. For example, climate change may alter freshwater thermal regimes, reduce ice cover in lakes, alter riverine flow regimes, increase water salinity due to increased desiccation, and potentially lead to increased reservoir construction required for water storage[158]. These changes may thus influence the numbers of potential non-native colonists, the probability that they will become established, and their environmental impact[158]. Indeed, climate change may force us to redefine what is meant by 'non-native' species in that species spatial ranges may change in response to a warming climate, indicating yet again the non-stationarity in ecosystem functioning. In addition, a vigorous debate is still ongoing as to exactly how the detrimental, or advantageous, effects of introduced non-native species are viewed and assessed[158,159], with dispute as to the existence and status of 'novel' or 'hybrid' ecosystems. This again calls for a more holistic monitoring of large riverine habitats to quantify these effects.

Fragmentation

In addition to natural barriers, such as waterfalls, steep cascades and canyons, the fragmentation of large river networks is being increasingly driven by anthropogenic factors, principally damming, canals and culverts, water extraction/hydrologic change, river interlinking, pollution (physical, chemical or thermal) and the introduction of non-native species[22,160]. These agents of fragmentation create habitat effects that may extend over different spatial scales and have differing upstream and downstream edge habitats or permeability (Supplementary Fig. 5). It is also likely that the temporal ecological response to implementation of a fragmentation node will be lagged, such that the effects of river fragmentation are probably underestimated at present[160].

Many studies have highlighted the significant effects of river fragmentation[74,160–163], and new models are providing more detailed and nuanced methods by which to assess future fragmentation, with a view to aiding sustainable dam and river basin development. For instance, recent modelling[74] has examined the potential influence of river fragmentation, a measure of structural connectivity within a river basin (river fragmentation index (RFI)), and river regulation, defined as alterations to the natural flow regime (river regulation index (RRI)) (Supplementary Fig. 5b,c). Predictions at the basin and sub-basin scale to the year 2030, and assuming all dams planned or under construction in 2014 would be built (Supplementary Fig. 5b,c), show potential substantial losses in connectivity in the Salween, Irrawaddy, Mekong, Amazon and Upper Nile rivers, with hot spots of flow regulation present in the Indus, Brahmaputra, Salween and Changjiang basins[74]. Such models provide considerable promise at a basinal scale[164] for examining the potential effects of dams, both singly and in groups, assessing the effects of dam position within the river network and the sequencing of construction on hydrological alterations.

Sediment dredging, mining and bank erosion

The world's great rivers are the arterial trade routes on which human civilization has developed, and, as trade has grown, so has the need for greater access for shipping and navigation, as well as exploiting river sediments for construction materials and land reclamation. These two uses also pose considerable issues. Firstly, the need to ensure passable navigation channels, whilst essential economically within many large river basins, may lead to concerns regarding hydrologically sensitive regions, and especially wetlands such as the Sudd on the Nile River in Southern Sudan[165] and the Pantanal on the Paraná River in Paraguay[166–168], that could be adversely affected by dredging or flow diversions. Secondly, sediment mining (Supplementary Fig. 6) may contribute significantly to decreasing downstream sediment flux, which may exacerbate the effects of subsidence in river deltas, as well as causing scour around in-channel engineering structures[169–171] and potentially triggering channel incision[172] and bank failures. For example, on the Zhujiang (Pearl) River, China, channel incision of up to 10 m over a period of 10 years has been ascribed largely to the effects of sand mining, which removes *c.* 60 Mt yr^{-1} (ref. [170]) — a value close to the annual suspended sediment load and more than four times the estimated annual bedload flux. This incision has been argued[170] to have resulted in: (1) reduced flood peaks, but a reduction in floodplain water retention; (2) increased economic costs in providing a drinking water supply; (3) threats to embankment and bridge infrastructure through enhanced scour; (4) changed aquatic habitats due to removal of bed material; (5) a lowered water table; and (6) enhanced intrusion of the salt wedge into the lower delta plain channels. The mid-lower Changjiang River has also seen increases in sediment extraction, from *c.* 40 Mt yr^{-1} in the 1980s to *c.* 80 Mt yr^{-1} in the late 1990s (ref. [171]), with its annual suspended sediment flux being *c.* 470 Mt yr^{-1} (Table 1) and bedload probably comprising *c.* 10–15% of this value (*c.* 45–70 Mt yr^{-1}). Thus, *c.* 17% of the total annual suspended sediment flux, or *c.* 90–170% of the bedload flux, may be being extracted. Likewise, estimates of sediment extraction from the Mekong River[172,173] yield figures of *c.* 55 Mt yr^{-1} (ref. [173]), with recent assessments[88] of the suspended sediment flux from the Mekong River being *c.* 87 ± 29 Mt yr^{-1} (with bedload an additional *c.* 10–15% of this figure, *c.* 9–15 Mt yr^{-1}). These figures indicate that the quantity of sediment being extracted from the Mekong River may be between 47% and 95% of the total annual suspended sediment load, or between *c.* 350% and 600% of the estimated bedload flux, with perhaps up to 10 times the annual sand load of the Mekong River being extracted[172]. Such sediment extraction has been linked to channel change on both rivers, with morphological change and infrastructure effects on the Changjiang River[171] and channel deepening, riverbank erosion and salt-wedge intrusion on the Mekong River[174]. Although the focus on reduced sediment supply in these rivers has often focused on the effects of dams[174], it is clear that in-channel sediment mining may pose a significant threat to sediment flux, channel stability and downstream delta sediment replenishment.

The issue of natural bank erosion is also significant in many large rivers, and can lead to severe loss of infrastructure and population displacement. Such issues are exemplified by the Jamuna River, Bangladesh, where bank erosion rates can approach 1 km yr^{-1} (ref. [175]) and generate a mobile population of char-dwellers who are displaced by such land loss[176]. Increased flood duration and magnitude, as well as sediment starvation, may exacerbate such bank erosion, with engineering schemes being required to protect key infrastructure[176,177], such as population centres, bridges and channel diversions. Quantification of decadal-scale patterns of bank erosion has been aided by remote sensing data and analysis[178], that can help direct bank protection schemes[179]. In addition, recent engineering approaches that advocate the use of sand-filled geotextile bags[180], rather than concrete blocks or aggregate, are enabling easier and more cost-effective bankline protection, especially in regions where such measures may always be required.

The governance of large rivers

The lens through which management decisions concerning large rivers are made has its focal point in the arena of politics and governance (the collaboration of civil society groups and government agencies[181]), and the overarching structure of social, financial, institutional, environmental and even religious frameworks[182]. Any meaningful implementation of policy has thus to be integrated[183] and embedded within these agendas, especially given that many of the world's great rivers are transboundary[9]. This context is fraught with considerable challenges, especially where large-scale boundary conditions, such as climate change[14,184,185], are uncertain. As such, the integration of governance has been viewed as perhaps the most difficult barrier to integrated river basin management[183]. In addition, such integrated water management must encompass issues of social equity, inclusivity, education and gender, which are essential at all scales to achieve sustainable water management strategies[181].

A recent synthesis[9,17] of the world's transboundary river basins has estimated rank indices for risks arising from legal framework, hydropolitical tension and the capacity for water governance at a national level. These variables yield a governance index that is set by the maximum relative risk in either of these categories (Supplementary Fig. 7), adopting the assumption that governance capacity is limited by the maximum risk attribute in the river basin[9]. Although not indicative of precise risk in each basin, this index shows that the Amazon, Congo, Irrawaddy, Salween and Yukon rivers are in the top two categories of governance risk, and are regions that face significant issues in basin management.

Two of many possible examples are worthy of mention herein. Efforts to combat pollution in the Changjiang and Ganges basins, two of the world's most polluted rivers in the globally fastest growing economies, have met substantial challenges[186]. Although these basins are largely non-transboundary, challenges arise from a lack of comprehensive legal mechanisms to regulate pollution on a basinal scale, an absence of co-ordination between governmental agencies and gaps in policy implementation[186]. This suggests[187] that China may require better co-ordination between agencies across organizational levels and sectors, improved monitoring of water quantity, quality and use efficiency, fuller integration of social sciences into water use planning and enhanced international cooperation, including reducing its water footprint. In addition, grassroots involvement is also essential[188] in developing awareness and action to address China's water sustainability.

A second example lies in the long and complex history of regulating the transboundary Nile River[1,189–194] that is shared by 14 riparian states[9] (Supplementary Table 1). Regional governance of the Nile basin has been dominated in the past by Egypt[193], and has witnessed a number of basin-wide co-operative institutions and treaties[189], including the 1929 British–Egyptian agreement, 1959 Nile Waters Agreement, Nile Basin Initiative signed in 1998, and 2010 Cooperative Framework Agreement[190]. However, the different scenarios for basin-wide governance have changed radically recently, as a result of political developments in the region, changing sources of funding for large-scale infrastructure and especially development of the Grand Ethiopian Renaissance Dam (GERD) that is slated for completion in 2018 (ref. [195,196]). GERD promises to change Egypt's previous dominant role on basin water management[193] and raises challenges to water security and political interactions in the region[197], but has the potential to produce a more equitable order in the Nile River basin[192,193,196,198].

The state of the world's big rivers: future developments

The world's big rivers face a range of stressors, yielding rates of change never witnessed before, as increasing demographic, water and economic requirements place ever-growing demands and challenges to their use. Although big rivers face pressing challenges, progress is being made towards providing the tools needed to address several of these issues.

The measurement of water discharge and water storage has been notoriously difficult for many large rivers, but new remote sensing techniques[199–203] are making the availability of such data possible and promising a global measurement network in the next decade. The Surface-Water Ocean Topography (SWOT) Mission[204], due for satellite launch in 2020, promises to revolutionize quantification of water level in global rivers over 100 m in width. Such remote sensing will permit monitoring of water discharge in both remote areas and in regions where such data may be politically and economically sensitive, potentially fostering trust between nations such as in the Nile River basin[196]. Likewise, such remote sensing offers new possibilities to quantify the flux of suspended sediment within large rivers[205] if ground calibration is possible, with recent research also developing new methods for remote bathymetric measurements, albeit in shallow smaller rivers at present[206]. In addition, recent advances in modelling sediment and nutrient flux from the world's large rivers[207–210], as well as longer term large river channel change[211,212], have made enormous progress. These advances promise to provide more holistic measures across large spatial and temporal scales, and help foster global flood risk networks[202], which will open a new era in large river management[213] where various scenarios of change can be modelled and used to inform and guide management decisions[21]. For example, consideration of the location and sequencing of dam construction can yield design strategies to help reduce downstream sediment starvation[214] (see Supplementary Fig. 1).

Expanding populations, and their reasonable aspiration for economic and social development, fuel demands on the ecosystem services of the world's big rivers. Such demands are particularly acute in the Global South, where many of the world's big rivers and large populations are located, and where environmental change is currently more rapid. Resource allocation to achieve such economic growth thus has to be traded off against environmental degradation, and needs to be viewed within the context of social justice in which resources need not necessarily be exploited more intensively if they could be distributed more equitably. This framework thus demands functioning social, economic and political structures to achieve such sustainable development. For example, much is being accomplished through transboundary river commissions, such as for the Danube (https://www.icpdr.org/main/), Nile (http://www.nilebasin.org/) and Mekong (http://www.mrcmekong.org/) rivers, and international organizations such as the World Resources Institute (https://www.wri.org/), Worldwatch Institute (http://www.worldwatch.org/), UN Water (http://www.unwater.org/), Transboundary Waters Assessment Program (http://www.geftwap.org/), Global Runoff Data Centre (https://www.bafg.de/GRDC/EN/Home/homepage_node.html), UNESCO (https://en.unesco.org/ihp-wins), International Rivers (https://www.internationalrivers.org/), International River Foundation (http://riverfoundation.org.au/) and World Wildlife Fund (https://www.worldwildlife.org/), and their database compilations.

The issue of resource exploitation thus raises the central question as to the degree of environmental change that a river can undergo while still retaining its ecosystem services. For most of the world's big rivers, the question is not 'what type of river regime can we return to that is identical to a state in the past?', especially in the light of the non-stationarity of processes highlighted above, but rather 'how can we define and implement a regime that can sustain the ecosystem services of a river?'. In the past 20 years, the development of thought and management tools based on 'environmental flows'[215–221] has opened new avenues to address this latter question. An environmental flow refers to the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems[222]. Developing thought and practice suggests that such flows may be based around a spectrum of flows of two broad types: (1) the paradigm of a 'natural flow' baseline[219,223] for rivers that are natural or semi-natural, and in which the primary objective is to maintain biodiversity and ecological integrity; and (2) where such a natural regime is not a realistic choice, designing flow regimes[219,221] to achieve specific ecological and ecosystem service outcomes. This latter approach is required in many of the world's big rivers in which substantial change has already taken place and that pose challenges to environmental flow assessments[215]. For example, such 'designer' flows can aim to build a flow regime to establish periods of high flow for channel maintenance and floodplain connections, and low flows of sufficient duration and correct timing to permit fish migration and spawning[221]. Recent research has also suggested the potential benefits of using designed water flow regimes from dams to restore and sustain ecosystems[224,225]. For example, more nuanced analysis for the design of river flows on the Mekong River[226] has considered the variance in shape of the annual flood hydrograph, and utilized spectral analysis to identify the dominant signals in the hydrograph that explain inter-annual variations in fish yield[225,226]. This data-driven approach suggests both the extent and variation of annual flood pulse are vital, and permits design of environmental flows that offer a route to balance fisheries yield with hydropower generation, rice production and transportation requirements. Although still contentious[227–229], such schemes promise the possibility of designing and implementing riverine flows that address the trade-offs between various ecosystem services. However, as highlighted previously, such schemes require adequate data on which to base such assessments[230,231]. In addition, successful design and implementation also necessitates the systematic integration of societal, political and economic frameworks and their practical use on the ground[232], in that selection of the 'desired ecosystem' is ultimately a matter of societal choice[221].

In a seminal call[233] in 1977, Luna Leopold appealed that we adopt a 'reverence for rivers' to hold them in the esteem they truly deserve. Such demands are partly embodied in the 2011 Vienna Declaration[234] on the Status and Future of the World's Large Rivers (WLRs), which called for a UNESCO-led "collaborative and multi-disciplinary international initiative to create the basis for a holistic, global scientific assessment of the state of the World's Large Rivers and promote urgently needed improved, integrated and sustainable management of WLRs and their surrounding landscapes and basins". The time is overdue to more fully enact upon such discussions, funding and management. The urgency of this task is demanded by the rapidity of change that some big rivers are undergoing, which is so massive that irreparable environmental changes will follow quickly. For example, pollution may have an instantaneous effect, non-native species may spread within years, and change associated with dam construction may appear within years to decades. Combined stressors may induce more rapid large-scale change, as suggested by a recent synthesis for the Mekong River basin[172] that contends that ecosystem collapse may be likely well before the end of this century. For some big rivers, it may already be too late, but for most the opportunity to seek alternatives to a range of anthropogenic stressors, or better plan their sustainable development, is still capable of ameliorating the effects of change. Such sustainable management must clearly be framed in a truly multidisciplinary context, and one that demands rapid integration of the science and engineering communities with local stakeholders, governmental planners and industry.

Data availability

Data and data sources for some of the data discussed in this paper are given in Supplementary Table 1.

Received: 27 March 2018; Accepted: 18 October 2018;
Published online: 17 December 2018

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Acknowledgements
I am indebted to C. Simpson for his exceptional graphical and database skills that were essential in preparing the figures, and I am very grateful for the provision of papers, figures and data from their own research by N. Arnell, P. Glennie, Y. Hirabayashi, D. Hoeinghaus, E. Latrubesse, H. Paltan and C. Zarfl.

I am also truly indebted to my colleagues who I have been incredibly fortunate to work with over many years, and who have provided considerable insights into, and opportunities to study, some of the world's largest rivers. Writing of this paper was aided by a Diamond Jubilee International Visiting Fellowship at the University of Southampton, UK, and its publication has been supported by the Jack and Richard Threet Chair in Sedimentary Geology at the University of Illinois, USA.

Competing interests
The author declares no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41561-018-0262-x.

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