a) Title Page

Scientists' Warning to Humanity on the Freshwater Biodiversity Crisis

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Authors: James S. Albert[1], Georgia Destouni[2], Scott M. Duke-Sylvester[3], Anne E. Magurran[4], Thierry Oberdorff[5], Roberto E. Reis[6], Kirk O. Winemiller[7], and William J. Ripple[8]

c) Author Biographies

[1] James S. Albert, Professor, Department of Biology, University of Louisiana at Lafayette. Lafayette LA, 70503, USA. Research interests: Freshwater ecology and conservation biology. Email: jalbert@louisiana.edu. ORCID: 0000-0001-5477-1749.

[2] Georgia Destouni, Professor, Department of Physical Geography, Bolin Centre for Climate Research, Stockholm University, Stockholm, 106 91, Sweden. Research interests: Hydrology, Hydrogeology and Water Resources. Email: georgia.destouni@natgeo.su.se. ORCID: 0000-0001-9408-4425.

[3] Scott M. Duke-Sylvester, Associate Professor, Department of Biology, University of Louisiana at Lafayette, Lafayette LA, 70503, USA. Research interests: Freshwater ecology and conservation biology. Email: smd3729@louisiana.edu.

[4] Anne E. Magurran, Professor, Centre for Biological Diversity, University of St Andrews, KY16, St Andrews, UK. Research interests: Freshwater ecology and conservation biology. Email: aem1@st-andrews.ac.uk. ORCID: 0000-0002-0036-2795

[5] Thierry Oberdorff, Professor, UMR5174 EDB (Laboratoire Evolution et Diversité Biologique) CNRS, IRD, UPS, Université Paul Sabatier, F-31062 Toulouse, France. Research interests: Freshwater ecology and conservation biology. Email: thierry.oberdorff@ird.fr. ORCID: 0000-0001-7323-2599.

[6] Roberto E. Reis, Professor, Department of Biodiversity and Ecology, Pontifícia Universidade Católica do Rio Grande do Sul, Porto Alegre, RS 90619-900, Research interests: Freshwater ecology and conservation biology. Brazil. Email: reis@pucrs.br. ORCID: 0000-0003-3746-6894.

[7] Kirk O. Winemiller, Professor, Department of Wildlife and Fisheries Sciences, Texas A&M University, College Station, TX 77843, USA. Research interests: Freshwater ecology and conservation biology. Email: k-winemiller@tamu.edu.

[8] William J. Ripple, Distinguished Professor, Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97330, USA. Research interests: Freshwater ecology and conservation biology. Email: bill.ripple@oregonstate.edu. ORCID: 0000-0003-0236-5129.

d) Abstract

Freshwater ecosystems provide irreplaceable services for both nature and society. The quality and quantity of freshwater affect biogeochemical processes and ecological dynamics that determine biodiversity, ecosystem productivity, and human health and welfare at local, regional and global scales. Freshwater ecosystems and their associated riparian habitats are amongst the most biologically diverse on Earth, and have inestimable economic, health, cultural, scientific and educational values. Yet human impacts to lakes, rivers, streams, wetlands and groundwater are dramatically reducing biodiversity and robbing critical natural resources and services from current and future generations. Freshwater biodiversity is declining rapidly on every continent and in every major river basin on Earth, and this degradation is occurring more rapidly than in terrestrial ecosystems. Currently, about 1/3 of all global freshwater discharges pass through human agricultural, industrial or urban infrastructure, and this proportion is projected to rise to about 1/2 of the world's freshwater flow capacity by the middle of the 21st century. About 1/5 of the Earth's arable land is now already equipped for irrigation, including all the most-productive lands, and this proportion is projected to surpass 1/3 by midcentury to feed the rapidly expanding populations of humans and commensal species, especially poultry and ruminant livestock. Less than 1/5 of the worlds preindustrial freshwater wetlands remain, and this proportion is projected to decline to under 1/10 by midcentury, with imminent threats from water transfer megaprojects in Brazil and India, and coastal wetland drainage megaprojects in China. The Living Planet Index for freshwater vertebrate populations has declined to just 1/3 that of 1970, and is projected to sink below 1/5 by midcentury. A linear model of global economic expansion yields the chilling prediction that human utilization of critical freshwater resources will approach 1/2 of the Earth's total capacity by midcentury. Although the magnitude and growth of the human freshwater footprint are greater than is generally understood by policy makers, the news media, or the general public, slowing and reversing dramatic losses of freshwater species and ecosystems is still possible. We recommend a set of urgent policy actions that promote clean water, conserve watershed services, and restore freshwater ecosystems and their vital services. Effective management of freshwater resources and ecosystems must be ranked amongst humanity's highest priorities.

e) Keywords:

Aquatic biodiversity, conservation, ecosystem services, freshwater, surface water, groundwater, wetlands.

f) Main text of article

The human freshwater footprint

Global civilization is reaching important boundaries of what the Earth's biosphere can support (Steffen et al. 2015). Human activities are altering the distribution and flows of surface, subsurface and atmospheric waters at regional scales, undermining the resilience of aquatic, riparian and coastal ecosystems (Rodell et al. 2018). In clarion calls published over the past quarter century (see Ripple et al. 2017; 2019) the world community of scientists has identified eight global and overlapping trends of environmental deterioration, all of immediate concern for human happiness and prosperity (Heino et al. 2009, Vörösmarty et al. 2010). Freshwater ecosystems are central to five of these trends: declining freshwater availability, forest loss, dwindling biodiversity, climate change, and human population growth. Although the profound consequences of anthropogenic activities on the biosphere are widely appreciated, freshwaters are often missing from the discussion (e.g. Lenton et al., 2019).

Freshwater (<500 ppm dissolved salts) is a renewable, but effectively finite, natural resource. Well-managed watersheds and waterbodies provide critical ecosystem services that maintain local and regional hydro-climatic regimes, and support human food and energy production, waste disposal and remediation, transportation, and recreation (Aldaya et al. 2012, Hoekstra and Mekonnen 2012). Freshwater ecosystems are also among the most diverse per unit habitat volume on Earth, with more than 140,000 species (i.e. fungi, plants, invertebrates, and vertebrates; c. 12% of all described species) compressed into just ~2% of the world's surface area, and a minute ~0.007% of the total planetary water supply (Reid et al. 2019). Freshwater species and ecosystems are increasingly threatened by many human activities, including habitat alteration, water pollution, overfishing, exotic species introduction, river diversions, fragmentation and flow regulation, expansion of agricultural and urban landscapes, climate change, rising sea levels and altered precipitation regimes (Dudgeon 2019, Grill et al. 2019; IPBES 2019).

Withdrawals and diversions (Jaramillo and Destouni 2015) as well as agricultural expansion and intensification (Destouni et al. 2013) are main threats to freshwater availability and quality (Destouni and Jarsjö 2018), while fragmentation and flow regulation (Winemiller et al. 2016) are main threats to freshwater biodiversity by altering rivers, floodplain lakes, wetlands and estuaries. Dams transform river basins by creating artificial lakes locally, fragmenting river networks, and greatly distorting natural patterns of sediment transport and seasonal variations in water temperatures and flows (Latrubesse et al. 2017). Altered flow seasonality in rivers has led to less diverse fish assemblages, decreased inland fisheries production, less stable bird populations and lower riparian forest production (Jardine et al. 2015, Kingsford et al. 2017, Sabo et al. 2017). Sediment retention by dams leads to delta recession (Luo et al. 2017) and degraded coastal fisheries and tropical mangrove forests, indirectly affecting carbon storage that reduces greenhouse gas emissions in the latter case (Atwood et al. 2017). Dams also prevent upstream-downstream movement of freshwater animals, facilitate settlement of non-native species, cause local species extirpations and replacements and increase risk of water-borne diseases in reservoirs and highly altered environments by modifying productivity (Fenwick 2006, Poff & Schmidt 2016). The fragmentation of river corridors also reduces population sizes and gene flows of aquatic species, increasing species extinction risks (Cohen et al. 2016, Dias et al. 2017).

At present humans divert >10,000 km^3 of freshwater per year for agriculture, industry and domestic uses, an amount that represents about 30% the average flow of all continental waters discharging to the sea or to recharge aquifers. The proportion of river discharge diverted for human activities exceeds 50% in the most densely populated areas of Eurasia. Water withdrawals and diversions currently cause about one-quarter of the world's rivers to run dry before reaching the ocean, and have drained major inland water bodies like the Aral Sea in Central Asia (Destouni et al. 2013) and Lake Urmia in Iran (Khazaei et al. 2019). Worldwide, agriculture accounts for about 70% of all freshwater usage, compared to 20% for industry and 10% for domestic uses (FAO 2016). Human-made dams and irrigation canals are associated with 12-16% of global food production and provide 19% of the world's electricity supply. The volume of water used by the energy sector alone represents about 15% of global freshwater withdrawals, and extracting and processing freshwater represents about 19% of total usage by the energy sector (Fricko et al. 2016). The amount of freshwater withdrawal varies substantially among regions, from <10% of total runoff in some counties at high latitudes with cold climates or in tropical regions with high rainfall, to >75% in arid areas of northern Africa, the Middle East and Australia (FAO 2016). Overall, the human freshwater withdrawals and diversions are now altering the distribution of water in the hydrosphere at regional scales. Damages are seen in the total area of anthropogenic (urban and agricultural) modified landscapes worldwide, wetlands reduction, and amount of surface and subsurface flows that have been diminished or degraded (Gleeson et al. 2016). The changes in water use, distribution and flows are combined with changes in climate and human population and land use, to impact biodiversity and ecosystem services (Elmhagen et al. 2015).

With regard to agriculture, just over 3 million km^2 are currently under cultivation worldwide, representing 22% of the total land area that is theoretically available for cultivation, with the most productive lands already long since under irrigation in most countries. Agricultural expansion and intensification in the landscapes increase evapotranspiration (Destouni et al. 2013) and thereby decrease the amount of freshwater runoff and aquifer recharge worldwide (Ceballos et al. 2015). Agricultural practices also degrade the quality and ecological status of the freshwater ecosystems, with status improvements remaining slow and difficult long after environmental regulations have been put in place requiring such improvements (Destouni et al. 2017).

Due to unprecedented socioeconomic advances and demographic shifts over the past 50 years (Crist et al. 2017), human and livestock population and economic growth are driving an ever expanding freshwater footprint (Fig. 1). Freshwater withdrawal and diversions for human uses have more than tripled since the middle of the 20th century, reducing the volume of river flow in more than half of the world's largest rivers. Increased human population and socio-economic activities also increase the pollutant and nutrient loads that deteriorate water quality and ecosystem status across different regions and countries around the world (Destouni and Jarsjö 2018, Levi et al. 2018).

Analysis of historical trends globally provided here shows that freshwaters are being depleted, and ecosystems degraded, even more rapidly than their terrestrial counterparts (Figure 1, Table 1). Measures of global freshwater withdrawals and total land-area equipped for irrigation are rising faster than the human use of terrestrial ecological productivity (Figure 1A). Similarly, rates of biodiversity loss are greater in freshwater than terrestrial ecosystems (Turak et al. 2017), and freshwater vertebrates (fishes and amphibians) are the most threatened group of vertebrates (Reid et al. 2013). Rates in the decline of both freshwater and terrestrial groups are also closely associated with extent of wetland loss (Figure 1B). The more rapid increase in threats to freshwater than terrestrial ecosystems arises from the minute total volume of liquid freshwater on the Earth's surface, and from the critical roles that freshwaters serve in human economic systems (Barbier et al. 2017).

Freshwater biodiversity is in sharp decline at many scales. Since 2000, abundances of freshwater insect (Sánchez-Bayo and Wyckhuys 2019, Wagner 2019) and fish populations organisms have become dramatically reduced, at local scales in both temperate (Freyhof and Brooks 2017) and tropical (Cohen et al. 2017, Pelicice et al. 2017) latitudes, and in different climate zones (Ngor et al. 2018). From 1970 to 2012 populations of vertebrate freshwater megafauna (defined as fishes, amphibians, reptiles and mammals ≥30 kg adult body weight) declined by 88%, with mega-fishes undergoing the largest declines (−94%, Carrizo et al. 2017; He et al. 2019). The Yangtze basin is among the most impacted of any large river on Earth, with the last citings of two species occurring in the 2000s; i.e. the Yangtze river dolphin †*Lipotes vexillifer* (Turvey et al. 2007), and the Yangtze paddlefish †*Psephurus gladius* (Zhang et al. 2009). The Yangtze paddlefish was the last surviving species of a lineage that originated in the super-greenhouse world of the Mesozoic, with fossils from the Upper Cretaceous about 75 million years ago. Examples of these and several other critically endangered freshwater megafauna species are illustrated in Fig. 2.

The levels of freshwater withdrawal and quality deterioration are well beyond levels that can support existing biodiversity, requisite ecological processes (Reid et al. 2018) or good ecological status, e.g. as required by the EU Water Framework Directive (Destouni et al. 2017). The largest imminent threats come from megaprojects designed to transfer water among river basins in Brazil and India (Shumilova et al. 2018), and to drain coastal wetlands in China (Cui et al. 2016). The total volume of water planned for near-future diversion megaprojects is projected to exceed 1,900 km^3 per year, representing an additional ~5% of total global surface freshwater flow (Shumilova et al. 2018). As of this writing ~4.0 billion people, or about two-thirds of the world population, experiences severe water scarcity, during at least part of the year (Mekonnen and Hoekstra 2016), and more than one-third of major urban areas globally (those with more than 3 million people) are experiencing high or extremely-high water stress (Sengupta and Cai 2019). Day Zero, the date when a city's water taps go dry, has been narrowly averted recently in São Paulo (Brazil), Chennai (India), Cape Town (South Africa), and Mexico City (Mexico).

The rapid rise of human populations and associated food production (e.g. crops and livestock) is increasing pressures on freshwater resources in many regions of the world. The total biomass of all humans alive today constitutes approximately 60 million metric tons of carbon, which is slightly more than 10 times that of all the remaining wild mammals of the world (Smil 2011). An unsustainable amount of freshwater is used to produce animal livestock. Global populations of domestic ruminants (cattle, sheep, and goats) (Ripple et al. 2013) poultry, and pigs (Bennett et al. 2018) used to feed the growing human population now exceed 100 million tons of carbon (Bar-On et al. 2018), and livestock populations are growing rapidly. Beef production alone consumes about 10 times more resources than other forms of animal protein. Domestic ruminant livestock (~4 billion globally) contribute 14.5% of all anthropogenic greenhouse gas emission, especially through the enteric fermentation by ruminants producing methane (Ripple et al. 2013). Ruminant livestock grazing is a direct cause of stream and wetland degradation in many areas (Beschta et al. 2013). Lowering the number of ruminant livestock would have the co-benefits of improving freshwater conditions and mitigating climate change.

The human utilization of both global freshwater and terrestrial resources shows persistent and linear increases over the past half century. A linear "business-as-usual" model is a significantly better fit to the historical data than models with curvilinear asymptotic growth (Fig.

1, Table 1). Such a linear model of global economic expansion yields the chilling prediction that human utilization of critical freshwater resources will approach and even exceed 50% of the Earth's natural supply by midcentury. It is possible for the human freshwater footprint to exceed the Earth's total freshwater capacity, at least transiently, through new technologically-mediated supplements; e.g. desalinated sea water for irrigation, transfer of marine productivity to fertilize terrestrial agroecosystems. Therefore, a linear growth model may be able to persist well into this century, despite the obvious crises that would follow as we reach or surpass the Earth's freshwater capacity.

Demands on global freshwaters continue to grow rapidly, with efforts to expand global food production by 50-70% before 2050 (FAO 2011, Molden 2007). In the 20th century, the human population grew fourfold and human appropriation of energy from the biosphere about doubled from 13% to 25% (Krausmann et al. 2013). The global human population is projected to reach 9.6 - 12.3 billion people by the year 2100, and the human appropriation of (terrestrial) net primary productivity (HANPP) to reach 40-60% (Krausmann et al. 2013). Therefore, by the time our grandchildren have grown up they must share the Earths' limited freshwater resources with 1.9 – 4.6 billion more people, or 25 – 60% more than the 7.7 billion people who live in the world today. The world that our grandchildren will inherit will be thirsty.

Recommended actions for freshwater biodiversity

Slowing and reversing the dramatic losses of freshwater species and ecosystems is still possible. The most effective conservation management coordinates actions at local to regional and national to international levels of organization (Ceballos et al. 2015), commensurate with the geographic distributions of species and ecosystems (Magurran 2016). Because many watersheds and all climate zones cross national boundaries, many environmental actions must be designed within international frameworks, and within the socioeconomic and ecological contexts of temperate (Allan and Watts 2018, Elmgren et al. 2015, Udall 2017) and tropical (Campos-Silva and Peres 2016, Cooke et al. 2016, Irvine et al. 2016) climates. Table S1 provides a list of major wetland and other freshwater management units for which effective conservation, preservation and restoration actions have been proposed or enacted. These management units represent freshwater ecosystems on all Earth's continents and climate zones, and most of the major continental-scale river drainage basins.

The following summary of policy recommendations therefore includes actions at the local and community scales, and also calls for actions at national and international scales (Poff et al. 2016, Sterner et al. 2019). These actions are critical to maintaining vital global freshwater ecosystem services, avoid water stress and scarcity, and improve human quality of life metrics.

The most effective measures to reduce freshwater degradation and promote watershed conservation need to motivate stakeholders at the local level, including farmers, consumers, municipalities and corporations, using a combination of market-based and regulatory incentives together with technological innovation (Barbier 2017). These actions will require more effective public education (see examples in Cooke et al. 2013) as well as better documentation of: 1) changes in species abundances and geographic distributions, 2) how changes in species composition affect ecosystem processes, and 3) biodiversity in the earth’s few remaining unimpacted ecosystems as references for future restoration (Magurran 2016).

At the regional level actions must be prioritized in the interrelated areas of water use, energy use, and biodiversity conservation (D'Odorico et al. 2018). Regional freshwater priorities include: 1) setting limits for sustainable freshwater withdrawals and diversions for river basins and coastal aquifers (Aldaya et al. 2012), 2) halting expansion of water-transfer megaprojects

(Shumilova et al. 2018), 3) converting agroecosystems to crops suitable for regional precipitation regimes, 4) halting peatlands draining to protect their specific biodiversity and to avoid their transformation from greenhouse gas sinks to sources, 5) requiring environmental impacts of freshwater appropriations and diversions in regional estimates of human impacts use of net primary productivity, 6) integrating vegetative land-surface cover with surface water and groundwater flows into of hydrological assessments on the impacts of freshwater appropriations, diversions and nutrient/pollutant inputs, 7) reverse osmosis desalination of seawater using new technologies with reduced carbon and thermal footprints (e.g. Gude 2016), and 8) regulation of the use of streams and wetlands by livestock.

Regional energy sector priorities include: 1) phasing out intensive use of freshwater for natural gas extraction and processing, once-through cooling freshwater systems for nuclear, carbon capture and storage, and concentrating solar power technologies, and converting these systems to air and sea-water cooling, 2) investing in an alternative energy matrix including solar, tidal and wind energy, 3) evaluating hydroelectric power and biofuel production and their water impacts across different scales, locally, nationally and globally (Engström et al. 2019), and 4) requiring regional and basin-wide planning for dam placement to more effectively balance conflicting energy and biodiversity interests, removing inefficient dams near the end of their “lifespans” or that were ill-conceived in the first place, and systematically designing technical solutions to maintain the fluvial system connectivity for dams of all sizes (Winemiller 2016).

Regional biodiversity priorities include: 1) designing protected areas for the particular spatial and temporal complexities of freshwater ecosystems (Juffe-Bignoli et al. 2016, Finlayson et al. 2019), 2) improving adaptive management practices to rural economies in developing countries with proactive strategies involving local communities for managing inland fisheries

(Fluet-Chouinard et al. 2018), 3) enhancing long-term biodiversity and water quality monitoring programs (Destouni et al. 2017), 4) promoting restoration practices that increase the extent of protected freshwater wetlands and headwater streams, 6) adapting management design to continental aquatic ecosystems (Petts 2018) implementing conservation agriculture policies that increase the proportion of plant products relative to animal products in human food production chains (Hobbs et al. 2011), and 8) accelerating research into water treatment technologies that improve water quality and reduce pollution from domestic and industrial point sources and from diffuse agricultural (Brack et al. 2015) and legacy sources (Destouni and Jarsjö 2018).

Research agencies must increase investments to document freshwater biodiversity through field inventories and long-term support for natural history museums. We must improve incentives for biodiversity assessment and monitoring, coordinate data into searchable online databases, quantify biodiversity trends across space and time, and document the distribution and abundance of invasive taxa. We must establish standardized criteria for assessing freshwater ecosystem health and sustainability, the taxonomic, functional, phylogenetic and population genetic aspects of biodiversity, preventing introductions of non-native aquatic species and infectious diseases. Finally, we must document shifting baselines in conservation management and develop reliable metrics to assess community perceptions of what constitutes healthy freshwater ecosystems.

Swift action is needed at every level to limit further expansion of freshwater withdrawals and pollution, and river fragmentation and flow regulation. First and foremost, we must stabilize the global climate and human population growth (Steffen et al. 2015). The international community must work together to limit 21st century global warming to < 2°C, and further return the global temperature anomaly to < 1.5°C above pre-industrial levels (UNFCCC 2015, Rogelj et al. 2018, Schleussner et al. 2016). Slowing and reversing global climate change will require an historical transition to a post-carbon global economy through a combination of regulatory and market-based mechanisms. Among the most effective methods for stabilizing human population growth are to provide primary and secondary education for girls, and voluntary family planning education for women in developing countries (Leigh and Blakely. 2017).

International actions with the greatest potential for rapidly reducing freshwater withdrawals and pollution include developing trans-boundary water-sharing and pollution mitigation agreements, and transferring efficient irrigation and water treatment technologies to developing countries in tropical regions. These countries expect the greatest increases in human density and per-capita water consumption in the next 50 years. However, we must not relocate agricultural and bioenergy production from high-income to low-income tropical regions, which will further threaten species-rich tropical aquatic ecosystems.

Conclusion

Conservation actions are most effective when they are implemented with full recognition of the genuine fragility of ecosystems. An ounce of conservation prevention is worth a pound of technological cures (Damania et al. 2019). We must realize that some changes are irreversible, such as species extinctions and ecosystem regime shifts (Hughes et al. 2013). We currently have technologies to manage and ameliorate many aspects of the freshwater biodiversity crisis — what we lack is political will. Political will by our policy makers, which in democratic societies means political will by the people who elect the policy makers; i.e. the citizens. A world with diminished freshwaters will impoverish many aspects of human welfare, and we risk further damaging these essential life-support systems at our peril. The time to act is now.

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h) Figures. Tables

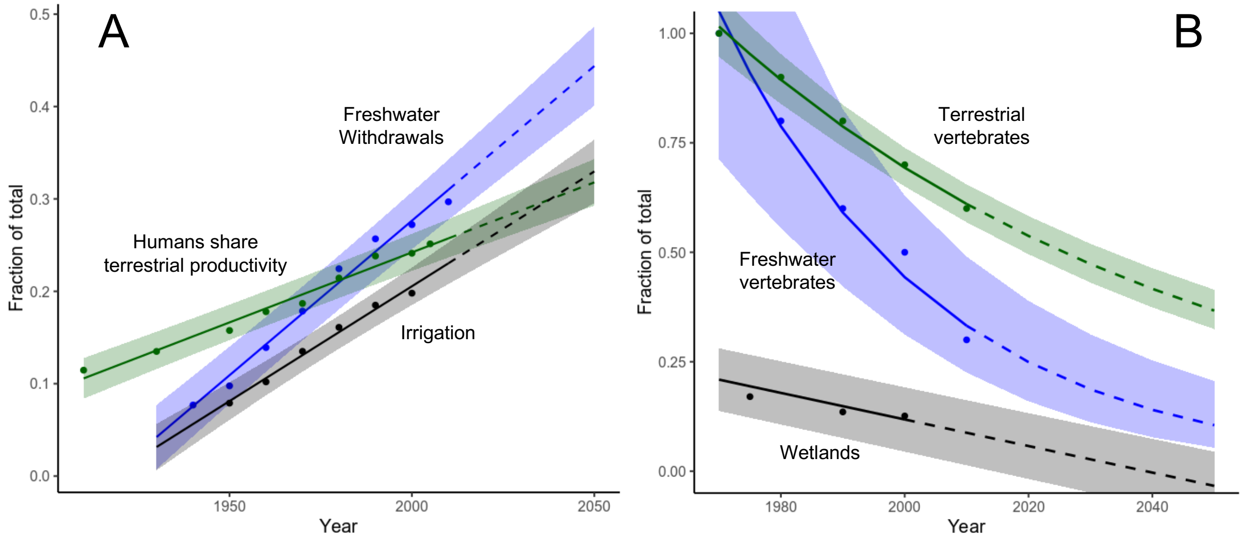


Figure 1. The expanding human freshwater footprint. **A.** Trends in global freshwater resources, assessed as Global Freshwater Withdrawals (blue) and Global Area Equipped for Irrigation (gray). Trend in terrestrial resources assessed as Human Appropriation of Terrestrial Net Primary Productivity (green). Note freshwater utilization is now a stronger limiting factor on human populations than terrestrial utilization. **B.** Trends in global biodiversity from a 1970 baseline. Living Planet Index for freshwater vertebrate populations (blue), for terrestrial vertebrate populations (green), and Global Wetland Loss (gray). Global Wetland Loss model fitted to data from 1700 to 2000 and plotted from 1970 to 2050 for compatibility with Living Planet Index datasets. Note rate of biodiversity decline is faster in freshwater than terrestrial systems, and occurring alongside reductions in Global Wetland Loss. The linear model projects global wetlands to disappear entirely by mid-century. Historical estimates as solid curves with 95% prediction intervals. Data as cumulative proportions of global totals. See footnote for methods.

Footnote to Figure 1: Methods for model specifications used to generate future projections (dashed curves) and literature references. Global Freshwater Withdrawals for human use as percentage of total annual river discharge to the sea (*c.* 36,000 km^3) (Milliman and Farnsworth 2013, van Vliet et al. 2013). Historical estimates from (Scanlon et al. 2007, Shiklomanov and Rodda 2004) adjusted to match the revised human-withdrawal estimate for 2010 of 10,688 km^3 yr^1 (Jaramillo and Destouni 2015). Irrigation as global area equipped for irrigation or land ready for cultivation as a percentage of total global arable land (*c.* 14 million km^2). Historical estimates from (Ellis et al. 2010, Scanlon et al. 2007, Siebert et al. 2015). Historical estimates of human share of terrestrial net primary productivity from (Krausmann et al. 2013). Population trends as estimated from the Living Planet Index (LP1 from Loh et al. 2005, WWF 2016) evaluated against a 1970 baseline. LPI measures trends in the geometric mean of population abundances. LPI-FW estimates from 3,324 monitored freshwater populations representing 881 species (darker curve with circles), and LPI-T for 4,658 terrestrial populations of 1,678 species (lighter curve with triangles). Note freshwater populations declined an estimated 81% from 1970 to 2012. Wetlands as percentage of pre-industrial total global wetland area at 1700. Historical estimates from (Davidson 2014.).

Table 1. Summary of models used to generate curves in Figure 1. Note that the historical data abstracted from literature reports used to fit these models do not include estimates of the variability for values at each data point. Therefore, the R^2 and p-values have limited utility as estimates of the fit between the models and the data used to generate the models, and the prediction intervals underestimate the true values of future uncertainty. Abbreviations: GWW, Global water withdrawals; HANPP, Human Appropriation of (terrestrial) Net Primary Productivity; GAEI, Global Area Equipped for Irrigation; LPI-FW, Living Planet Index-Freshwater; LPI-T, Living Planet Index-Terrestrial; GWL, Global Wetland Loss.

Trend	**Model**	**R^2**	**p**
GWW [a]	= -6.41 + 0.0033 Year	0.98	1.20E-06
HANPP [b]	= -2.78 + 0.0015 Year	0.98	3.90E-07
GAEI [c]	= -4.77 + 0.0025 Year	0.98	6.20E-05
ln(LPI-FW) [d]	= 56.7 - 0.029 Year	0.97	0.0025
LPI-FW [d]	= 4.2e24 e-0.029 Year	0.97	0.0025
ln(LPI-T) [e]	= 25.1 - 0.013 Year	0.99	0.00018
LPI-FW [e]	= 8.0e10 e-0.013 Year	0.99	0.00018
GWL [f]	= 6.19 - 0.003 Year	0.99	4.90E-07

Footnotes to Table 1:

[a] Global Water Withdrawals (GWW) for human use as percentage of total annual river discharge to the sea (*c.* 36,000 km^3) (Milliman and Farnsworth 2013, van Vliet et al. 2013). Historical estimates from (Scanlon et al. 2007, Shiklomanov and Rodda 2004) adjusted to match the revised human-withdrawal estimate for 2010 of 10,688 km^3 yr^1 (Jaramillo and Destouni 2015).

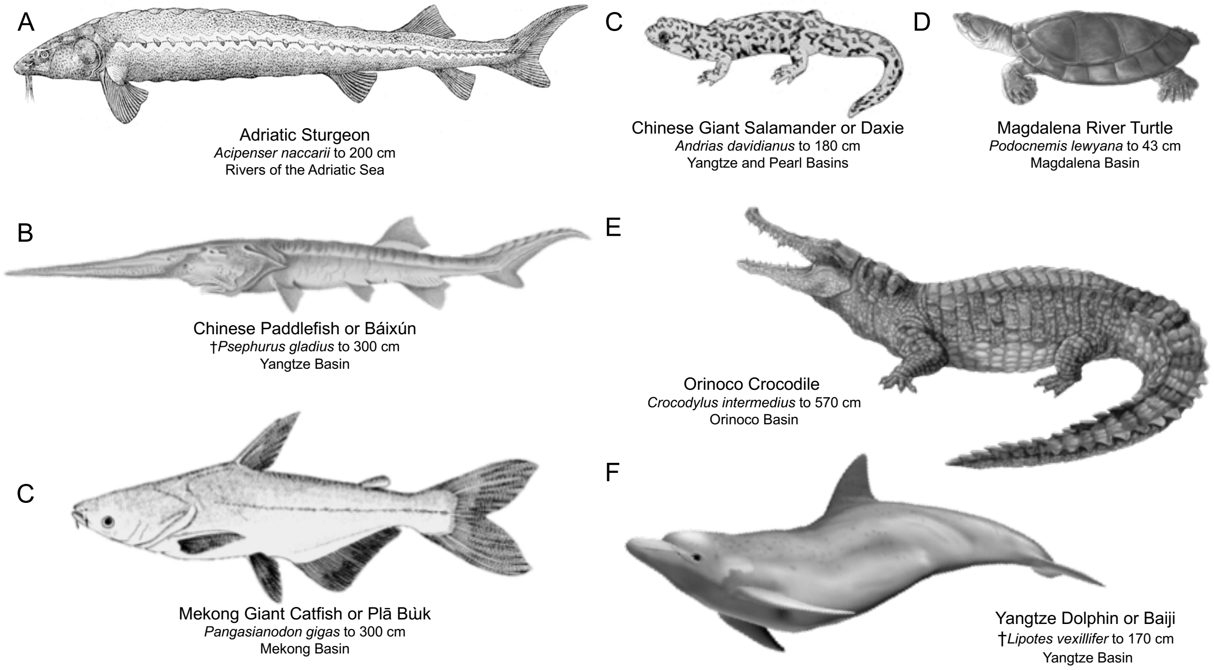
[b] Historical estimates of Human Appropriation of (terrestrial) Net Primary Productivity (HANPP) from (Krausmann et al. 2013). Population trends as estimated from the Living Planet Index (Loh et al. 2005, WWF 2016) evaluated against a 1970 baseline.

[c] Global Area Equipped for Irrigation or land ready for cultivation as a percentage of total global arable land (*c.* 14 million km^2). Historical estimates from (Ellis et al. 2010, Scanlon et al. 2007, Siebert et al. 2015).

[d] LPI measures trends in the geometric mean of population abundances. LPI-FW estimates from 3,324 monitored freshwater populations representing 881 species. Note freshwater populations declined an estimated 81% from 1970 to 2012.

[e] LPI-T estimates 4,658 terrestrial populations of 1,678 species.

[f] Global Wetland Loss (GWL) as percentage of pre-industrial total global wetland area at 1700. Historical estimates from (Davidson 2014.).



Adriatic Sturgeon
Acipenser naccarii to 200 cm
Rivers of the Adriatic Sea

Chinese Giant Salamander or Daxie
Andrias davidianus to 180 cm
Yangtze and Pearl Basins

Magdalena River Turtle
Podocnemis lewyana to 43 cm
Magdalena Basin

Chinese Paddlefish or Báixún
†*Psephurus gladius* to 300 cm
Yangtze Basin

Orinoco Crocodile
Crocodylus intermedius to 570 cm
Orinoco Basin

Mekong Giant Catfish or Plā Bṳ̀k
Pangasianodon gigas to 300 cm
Mekong Basin

Yangtze Dolphin or Baiji
†*Lipotes vexillifer* to 170 cm
Yangtze Basin

Fig. 2. Examples of critically endangered or recently extinct (†) freshwater megafauna (≥30 kg). Freshwater animals with large adult body sizes have higher extinction risk due to complex habitat requirements and slow life-history strategies (e.g. long life span and late maturity). The main conservation threats to these species come from human activities, including overharvesting, pollution, introducing invasive species, and habitat modifications (e.g. water diversions, land-use changes, climate change). The species illustrated roughly represent the proportions of endangered freshwater vertebrates, with greater threats to fishes (A-C) than to tetrapods (C-F), and to Eurasian (A-C, F) than non-Eurasian (D-E) species. Image sources: *Acipenser naccarii,* †*Psephurus gladius, Andrias davidianus* from Wikimedia Commons; *Crocodylus intermedius* and *Podocnemis lewyana* from Threatened Reptiles of Colombia (http://reporte.humboldt.org.co/biodiversidad/); *Pangasianodon gigas* from Fishbase (https://www.pngguru.com/), †*Lipotes vexillifer* from pngguru (https://www.pngguru.com/).

Table S1. Major wetland and other freshwater management units for which effective conservation, preservation and restoration actions have been proposed or enacted. Biota = Plants, Crustaceans, Mollusks, Fishes, Amphibians, Reptiles, Mammals.

Continent	Area focus	Country/State	Management focus	Reference
Global	Urban ponds	Several	Biota, hydrology	Oertli & Parris, 2019
	Wetlands and rivers	Several	Invertebrates	Boix, 2018
	Wetlands and rivers	Several	Fisheries	McIntyre et al. 2016
	Wetlands and rivers	Several	Water resource management	Pittock et al. 2015
	Apex predators	Several	Fishes	Winemiller et al. 2016
	Protected areas	Several	Fishes	Pittock et al. 2018
	Rivers	Several	Water resource management	Schmutz & Sendzimir, 2018
Africa	Several areas	Africa	Biota	Fouchy et al. 2019
	Okavango	Botswana	Biota	Ioris, 2016b
	Okavango	Botswana	Fishes	Mosepele et al. 2017
	Congo River Basin	Cameroon	Water resource management	Ako et al. 2010
	Lake Chad basin	Chad	Fishes	Lemoalle et al. 2012
	Lake Chad basin	Chad	Remote sensing	Onamuti et al. 2017
	Lake Malawi	Malawi	Fishes	Kafumbata et al. 2014
	Nile	NE Africa	Fishes	Allan et al. 2019
	Lake Victoria	Tanzania	Fisheries	Eggert & Lokina, 2010
Asia	Coastal wetlands	China	Vegetation, hydrology	Cui et al. 2016
	Peatlands	India	Vegetation, hydrology	Cheyne & Macdonald, 2011
	Peatlands	Indonesia	Vegetation, hydrology	Uda et al. 2017
	Natural lakes & reservoirs	Indonesia	Fishes	Kurniawan & Subehi, 2016
	Peatlands	Indonesia	Vegetation, hydrology	Wösten et al. 2006
	Lake Urmia	Iran	Hydrology, land-use	Khazaei et al. 2019
	Japan	Japan	Fisheries	Rahel & Taniguchi, 2019
	Aral Sea	Kazakhstan, Uzbekistan	Climate models	Destouni et al. 2013
	Aral Sea	Kazakhstan, Uzbekistan	Biota, hydrology	Micklin, 2016
	West Siberia Peatland	Russia	Ecosystem services	Keddy et al. 2009
	Endorheic basins	Several	Hydrology	Yapiyev et al. 2017
	Nee Soon forest	Singapore	Macroinvertebrates	Ho et al. 2018
	South Korea	South Korea	Fishes	Kwon et al. 2015
Australia	South East Queensland	Australia	Water resource management	Mantyka-Pringle et al. 2016

	Australian rivers	Australia	Land-use policy	Hermoso et al. 2016
Europe	Loire basin	France	Fishes	Bergerot et al. 2008
	Mediterranean	Several	Biota, hydrology	Céréghino et al. 2007
	Danube river	Several	Water resource management	Hein et al. 2016
	Iberian rivers	Spain, Portugal	Fishes	Hermoso et al. 2018
	Iberian rivers	Spain, Portugal	Fishes	Maceda-Veiga, 2013
	Swedish rivers	Sweden	Water resource management	Malm-Renöfält et al. 2010
New Zealand	New Zealand rivers	New Zealand	Water resource management	West et al. 2019
North America	Californian river and wetlands	California	Water resource management	Howard et al. 2018
	Sacramento Delta	California	Plants	Sloey & Hester, 2019
	Mackenzie River Basin	Canada	Water resource management	Saunders, 2014
	Hudson Bay Lowland	Canada	Biota, hydrology	Abraham & Keddy, 2005
	Mackenzie River Basin	Canada	Fisheries	Poesch et al. 2106
	Artic rivers & wetlands	Canada	Fishes	Culp et al. 2012
	Everglades	Florida	Vegetation, hydrology	D'odorico et al. 2013
	Tennessee & Cumberland rivers	Kentucky, Tennessee	Water resource management	Thieme et al. 2012
	Louisiana coastal wetlands	Louisiana	Plants	Yando et al. 2019
	Gulf Coastal Plain	USA	Birds	Nyhus et al. 2018
	Mississippi river	USA	Water resource management	Gore, 2018
South America	Magellanic moorland	Argentina, Chile	Plants, Birds, Mammals	Arroyo et al. 2005
	Mamirauá Reserve	Brazil	Fisheries	Campos-Silva & Peres, 2016
	Mamirauá Reserve	Brazil	Birds	Costa, 2016
	Several areas	Brazil	Fishes	Alho et al. 2015
	Amazon	Brazil	Plants, Fishes	Reis et al. 2019
	Pantanal	Brazil, Paraguay	Water resource management	Ioris, 2016a
	Pantanal	Brazil, Paraguay	Biota	Tomas et al. 2019
	Andean rivers	Colombia, Ecuador, Peru	Fishes	Tognelli et al. 2019
	Pacaya-Samiria Reserve	Peru	Turtles	Harju et al. 2018
	Amazon rivers	Several	Energy resource management	Anderson et al. 2018
	Amazon rivers	Several	Land-use policy	Leitão et al. 2018
	Amazon rivers	Several	Vegetation, hydrology	Arantes et al. 2019
	Several areas	Several	Biota	Goulding et al. 2019

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