



Freshwater Resources and Biodiversity: From Competition to Synergy

Executive Summary



KFW



SENCKENBERG
NATURE RESEARCH

Freshwater resources and biodiversity: from competition to synergy

Executive Summary

Klement Tockner^{1,2}, Petra Döll^{1,3}, Mark O. Gessner^{4,5}, Peter Haase^{1,5},
Bernd Hansjürgens^{6,7}, Robert Luetkemeier^{1,8}, Andrea Sundermann^{1,9}, Christiane Zarfl^{10,11}

¹ Senckenberg – Leibniz Institution for Biodiversity and Earth System Research, Frankfurt, Germany

² Goethe University Frankfurt, Department of Biosciences, Frankfurt am Main, Germany

³ Goethe University Frankfurt, Institute of Physical Geography, Frankfurt am Main, Germany

⁴ Leibniz Institute of Freshwater Ecology & Inland Fisheries (IGB), Department of Plankton and Microbial Ecology, Stechlin, Germany

⁵ University of Duisburg-Essen, Faculty of Biology, Essen, Germany

⁶ Helmholtz Center for Environmental Research (UFZ), Research Unit “Environment and Society”, Department Economics, Leipzig, Germany

⁷ Martin Luther University Halle-Wittenberg, Faculty of Law and Economics, Halle, Germany

⁸ Institute for Social-Ecological Research (ISOE), Research Unit “Water and Land Use”, Frankfurt, Germany

⁹ Goethe University Frankfurt, Institute of Ecology, Evolution and Diversity, Frankfurt, Germany

¹⁰ University of Tübingen, Environmental Systems Analysis, Department of Geosciences, Tübingen, Germany

¹¹ University of Tübingen, Cluster of Excellence: EXC 3121: TERRA – Terrestrial Geo-Biosphere Interactions in a Changing World, Tübingen, Germany

Freshwater is more than a resource

There can be no lasting water security without healthy freshwater ecosystems.

Water is foundational to the Earth system. It connects climate, biogeochemical cycles, biodiversity, food and energy supply, human health, culture and economic development. Despite its vital importance for human well-being and ecosystems, water is still largely managed as a resource (and, when in excess, as a hazard) to be controlled, extracted and allocated among often competing uses. Freshwater biodiversity and ecosystems are, at best, treated as just another competing demand. Instead, water must be managed as an interconnected social–ecological–technological system, in which ecosystem integrity and human water needs are addressed jointly and at eye level, rather than as competing priorities. The challenge is therefore not to balance water for people against water for nature, but to create lasting synergies between healthy freshwater ecosystems, human well-being and economic prosperity.

The Great Acceleration continues

The Great Acceleration has driven unprecedented gains in human prosperity, but at the cost of degrading the freshwater ecosystems and natural capital on which long-term prosperity depends. Continuing on this trajectory will further undermine freshwater biodiversity, water security and economic resilience, posing escalating risks to nature and society.

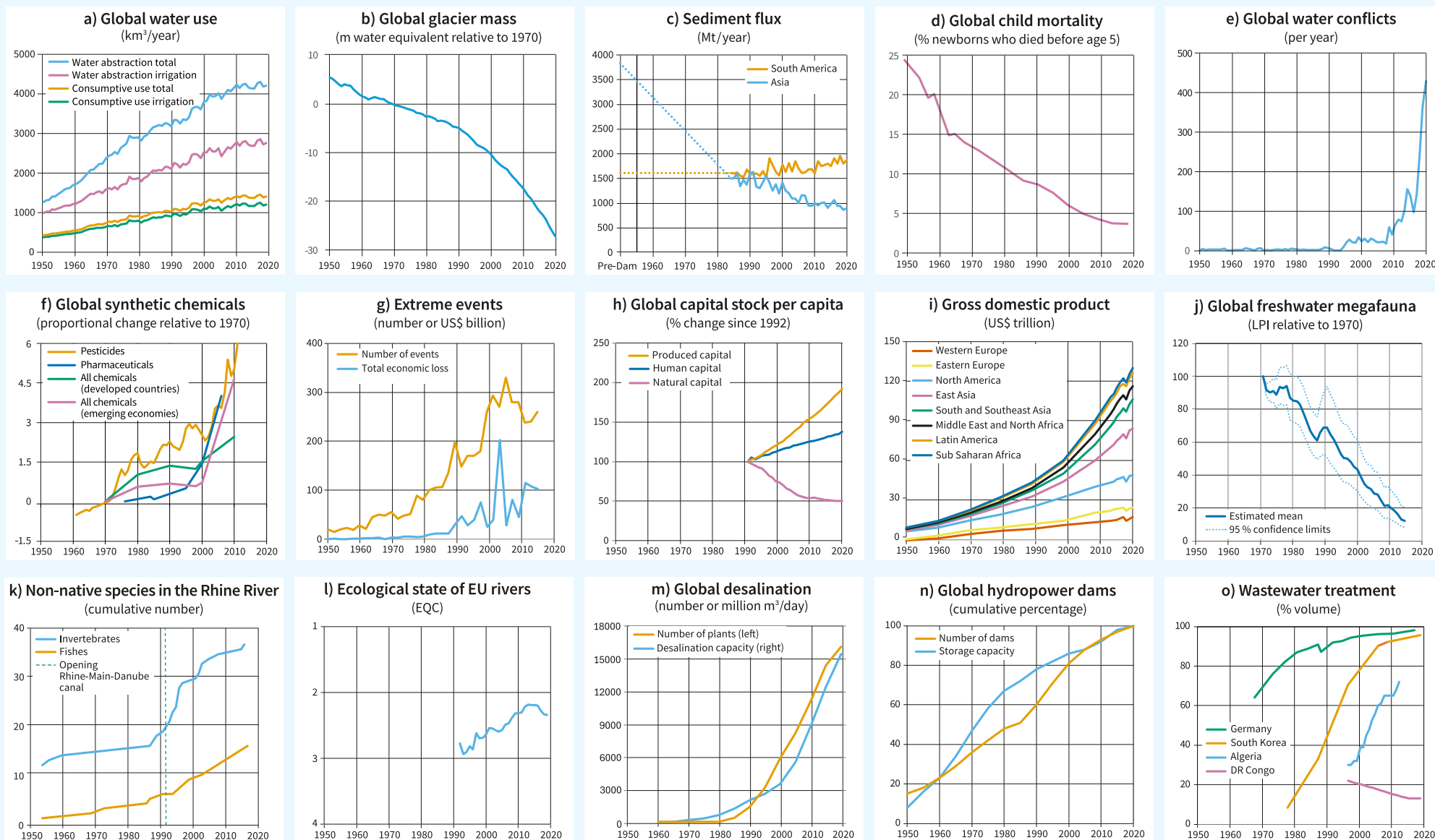
Seven decades of freshwater transformation reveal a fundamental imbalance. Remarkable advances in economic development, technology and public health have been accompanied by growing pressures on freshwater resources and severe biodiversity losses. The 15 graphs in [Box 1](#) illustrate these contrasting trajectories and their consequences for ecosystems, economies and societies. Rapid growth in water abstraction, chemical production and infrastructure development has coincided with accelerating glacier mass loss, altered sediment transport, collapsing freshwater megafauna populations and the spread of non-native species. At the same time, reported water-related conflicts and the economic costs of extreme events have risen.

However, progress is possible. Child mortality has declined dramatically, partly due to improvements in water supplies, access to sanitation and hygiene. Wastewater treatment

has expanded in many countries, and targeted conservation and restoration efforts have enabled freshwater biodiversity to recover in some regions, although major inequalities and environmental challenges persist. These developments demonstrate the potential of technological innovation, public investment and effective governance to deliver positive outcomes.

The central challenge is to achieve human well-being and economic prosperity without further eroding the freshwater ecosystems on which both depend. Technological efficiency and infrastructure expansion alone are insufficient to meet this challenge. Lasting water security and economic prosperity depend on protecting and restoring freshwater ecosystems, reducing environmental pressures and bringing human water use within the ecological limits of the global water cycle.

Box 1: Seven decades of freshwater transformation: growing human well-being, declining freshwater resources and biodiversity



Legend Box 1

Fifteen long-term trends illustrating changes in freshwater resources, environmental pressures, biodiversity, economic development and human well-being. The panels combine global indicators with selected regional and national examples, highlighting the contrasting trajectories of human development and freshwater ecosystem integrity.

a) Global water use. Long-term increases in global freshwater withdrawals and consumptive water use, distinguishing irrigation from total water use and illustrating the growing appropriation of freshwater to humans (WaterGAP, 2026; P. Döll, unpublished data).

b) Global glacier mass. Long-term decline in global glacier mass, expressed as cumulative changes in metres of water equivalent relative to 1970, illustrating the accelerating depletion of freshwater stored in glaciers (redrawn after WGMS, 2023).

c) Sediment flux. Contrasting long-term trends in riverine sediment transport in Asia and South America, expressed as annual sediment flux to the sea (Mt/year). Sediment delivery has substantially declined in Asia, largely due to sediment retention by dams, but has increased in South America despite continued dam construction, reflecting increased erosion that results from widespread land-use change. Pre-dam estimates provide historical references for comparison (redrawn after (Dethier et al., 2022).

d) Global child mortality. Long-term decline in the probability of child death before the age of five, expressed as a percentage of live births, reflecting major improvements in human health, nutrition, living conditions, medical care, sanitation and safe drinking water (redrawn after IHME 2025).

e) Global water conflicts. Annual number of recorded incidents involving water as a trigger of violence, a weapon during conflict, or a casualty of violence, including attacks on water resources and infrastructure. The trend documents a marked increase in reported water-related conflict events, particularly in recent years (redrawn after Pacific Institute, 2025; P. Gleick, 2026, personal communication).

f) Global synthetic chemicals. Long-term increases in indicators of global synthetic chemical production and use, including pesticides and pharmaceuticals, expressed relative to the respective baseline values in 1970. The trends illustrate the rapid expansion of chemical production and associated pressures on freshwater ecosystems (redrawn after Bernhardt et al., 2017).

g) Extreme events. Long-term trends in the number of recorded extreme meteorological events such as floods, and their associated reported economic losses (US\$ billion), illustrating the growing economic consequences of disasters (redrawn after WMO, 2023).

h) Global capital stocks per capita. Global changes in produced, human and natural capital per capita, indexed to 1992 (1992 = 100). While produced and human capital have substantially increased, the depicted indicator of natural capital has declined by 50%, highlighting the erosion of natural assets alongside economic development (redrawn after Dasgupta, 2021).

i) Global gross domestic product. Long-term growth in global GDP (US\$ trillion), differentiated by major world regions, illustrating the scale and geographical distribution of economic expansion (redrawn after Bolt & van Zanden, 2024).

j) Global freshwater megafauna. Long-term decline in the relative abundance of monitored freshwater megafauna populations, expressed as a Living Planet Index relative to 1970, illustrating severe population losses among large-bodied freshwater animals (redrawn after He et al., 2019).

k) Non-native species in the Rhine River. Cumulative number of recorded non-native invertebrate and fish species in the Rhine River. The opening of the Rhine–Main–Danube Canal in 1992 facilitated the spread of Ponto-Caspian species (redrawn after IKSIR et al., 2018, 2021).

l) Ecological state of EU rivers. Temporal development of the Ecological Quality Class (EQC) of rivers in the European Union (EU), indicating ecosystem integrity according to the EU Water Framework Directive (1992–2019), with the scores of 2 and 3 reflecting good and moderate ecological quality, respectively (redrawn after Sinclair et al., 2024).

m) Global desalination. Rapid expansion in the number of desalination plants and installed desalination capacity, illustrating the growing technological capacity to augment freshwater supplies from saline and brackish water sources (redrawn after Jones et al., 2019).

n) Global hydropower dams. Expansion of large hydropower dams and associated storage capacity, reflecting increasing fragmentation, shifts in hydrological regimes and other modifications of large rivers globally, despite recent dam removal initiatives (redrawn after Lehner et al., 2024).

o) Wastewater treatment. Contrasting long-term developments in wastewater treatment in Germany, South Korea, Algeria and the Democratic Republic of the Congo, illustrating substantial improvements in wastewater management in some countries and persistent gaps in others (compilation of data and redrawn after OECD, 1993, 2012, 2017, 2023; Statistics Korea/Ministry of Climate, Energy and Environment, National Sewerage Information System, 2026; Statistics South Africa, 2017, 2024; UNSD, 2026; WHO/UNICEF/JMP, 2025; Worldbank/AMCOW, 2011).

Freshwater biodiversity is under increasing pressure

Freshwater ecosystems are global hot spots of biodiversity, but one quarter of freshwater species is threatened with extinction.

Covering about 1% of the Earth's surface, rivers and lakes support around 10% of all known species and even one-third of all vertebrate species (Strayer & Dudgeon, 2010). The most comprehensive global assessment of freshwater fishes, odonates and decapods to date evaluated more than 23,000 species and found nearly a quarter of them (24%) to be at risk of extinction. Among the threatened species, 54% are affected by pollution, 39% by dams and water abstraction, 37% by agricultural land use and 28% by species invasions and disease. As many as 84% face more than one threat (Sayer et al., 2025). Monitored populations of migratory freshwater fishes have declined by 81% between 1970 and 2020, and once abundant iconic species of economic importance such as the European eel are at the brink of extinction. Only 37% of rivers longer than 1,000 km remain free-flowing over their entire length, most of them in remote areas such as Siberia and the Amazon basin (Deinet et al., 2024; Grill et al., 2019).

Global wetland decline further illustrates the ecological and economic consequences of human activities. Since 1970, around 411 million

hectares, equivalent to 22% of the global wetland area, have been lost, and approximately 25% of the remaining area is in poor condition. Despite these losses, the remaining 1.4 billion hectares provide ecosystem services valued at US\$ 8 trillion annually under conservative assumptions, with higher estimates reaching US\$ 39 trillion (Convention on Wetlands, 2025). Continued wetland loss therefore threatens biodiversity and ecosystem integrity while depleting economically valuable natural capital.

Freshwater resources are rapidly declining

Human activities and climate change are fundamentally altering the quantity, quality, distribution and dynamics of freshwater resources across the planet.

Freshwater reserves are declining in many regions, while growing human populations and economic development increase demand. Human water use and climate change have reduced global freshwater reserves – including water stored in surface waters, groundwater, soil, snow and glaciers – by an estimated 324 km³ per year over the past two decades. Satellites can infer water storage changes from gravity anomalies, which indicate that human water use and climate change have led to mostly

irreversible changes (see [Figure 1](#)). Strong declines in water storage are due to human over-exploitation of water resources and glacier loss, while the smaller increasing trends are caused by precipitation increases.

Glaciers have lost approximately 6,500 billion tonnes of ice between 2000 and 2023, with the average annual loss rate increasing by 36% between 2000–2011 and 2012–2023. Glaciers and snowpacks are critical to sustaining freshwater flows, with 55–60% of global runoff generated in the world's mountains. Around two billion people, approximately a quarter of the world population, depend on mountain water resources. By 2100, 26–41% of mountain glacier mass is projected to be lost under warming scenarios of 1.5–4°C (The GlambIE Team, 2025; UNESCO WWAP, 2025).

Economic activities are major drivers of freshwater abstraction and degradation. Agriculture, energy production, mining, manufacturing, urbanisation and infrastructure development affect the quantity, quality, timing, distribution and connectivity of freshwaters, contributing to biodiversity loss and declining ecosystem integrity. Irrigated agriculture accounts for around 70% of global freshwater abstraction and around 90% of consumptive water use [McDermid et al., 2023; Gordon et al., 2010]. Global supply chains also redistribute pressures through the trade of virtual water, which is water used to produce

GSFC annual trend (2002–2025)

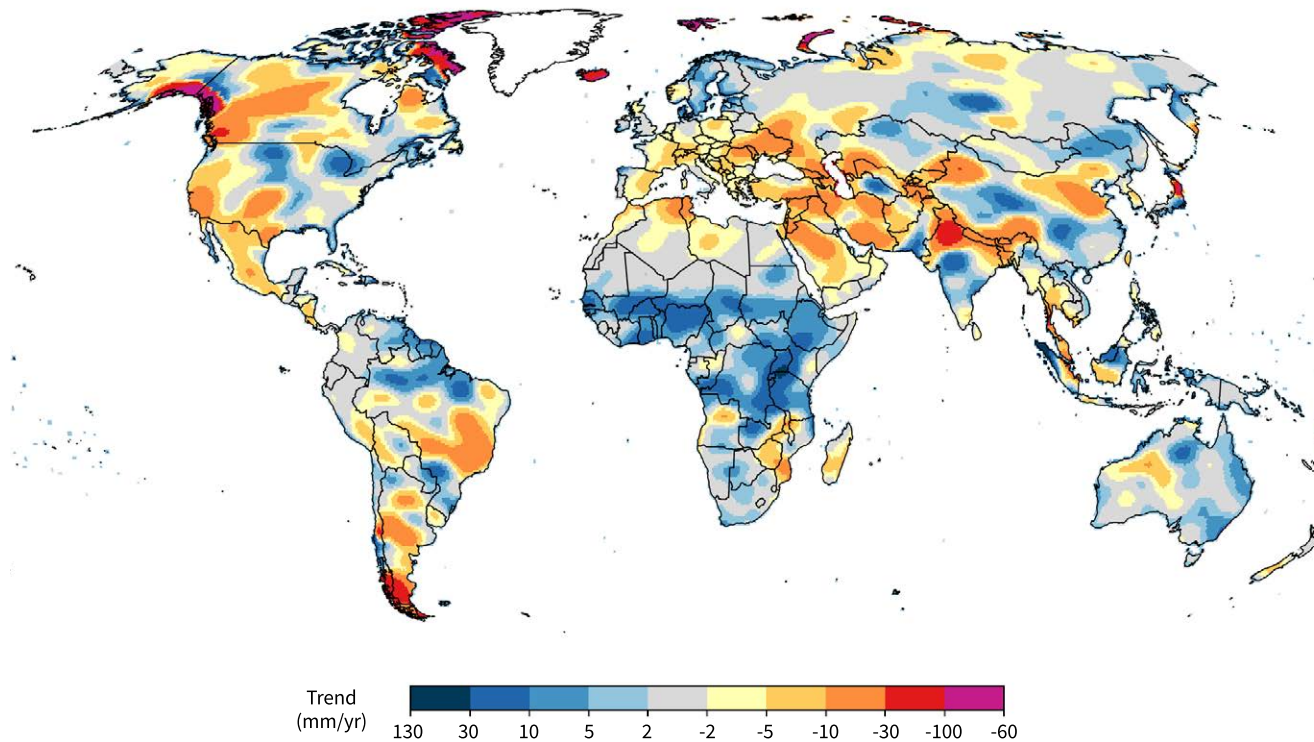


Figure 1: Average annual change in terrestrial water storage between 2002 and 2025 as derived from GRACE satellite observations. Trends were computed using the GSFC mascon product (Loomis et al., 2019). Please note that due to the large footprint of the satellite observations, the trends are spatially smoothed; actual trends are more localized and can be larger. Without climate change and human water depletion, the trends would be close to zero.

goods and commodities, shifting environmental impacts to regions often far removed from the consumers and markets driving demand.

Climate change amplifies these pressures by altering the distribution and timing of precipitation, evaporation, snow and ice storage, and the frequency and severity of hydrological extremes. Droughts, declining groundwater levels and the drying of rivers increasingly threaten water security, while intense rainfall and floods cause severe damage to infrastructure, livelihoods and human lives. Some changes, including groundwater depletion, salinisation, wetland loss and glacier retreat, can persist for decades to millennia and become effectively irreversible on human timescales. Climate adaptation must therefore address not only water supply and infrastructure, but also the capacity of freshwater ecosystems to retain water, buffer hydrological extremes, maintain water quality, and sustain biodiversity and ecosystem integrity under changing climatic conditions.

Freshwater biodiversity and the economy are mutually dependent

The degradation of freshwater ecosystems is increasingly a systemic risk to economies, public finances and human well-being.

The conventional distinction between “water for people” and “water for nature” is misleading, because human water security ultimately depends on intact freshwater ecosystems. Degraded freshwaters, characterised by pollution, altered hydrological and geomorphological conditions and biodiversity loss, tend to be less capable of purifying water, regulating flows, recycling nutrients, transporting sediments and buffering floods and droughts than unimpaired ecosystems. Freshwater biodiversity and ecosystem integrity are therefore not merely beneficiaries of effective water management, but essential contributors to water security and human well-being.

The relationship between economic activities and freshwater ecosystems is reciprocal. While economic activities are major drivers of freshwater degradation, economies also depend on the natural capital provided by freshwater ecosystems and are therefore highly vulnerable to freshwater depletion. Agriculture, energy generation, manufacturing, river navigation and cities rely on reliable water supplies, while freshwater ecosystems also support flood protection,

cooling, transport and other essential services. Global value chains further depend on freshwater resources and ecosystems in regions often far removed from final consumers.

Freshwater degradation therefore creates physical, economic and financial risks. Water scarcity, droughts, floods, pollution and ecosystem degradation can reduce agricultural and industrial productivity, constrain energy production and navigation, disrupt supply chains, damage infrastructure, increase commodity prices and public expenditure, and heighten credit, investment and insurance risks. In particularly dry years, crop yields can decline by up to 22%. Severe droughts can reduce hydropower generation by more than 25% and inland waterway freight volumes by up to 40% in Central and Eastern Europe, disrupting supply chains and industrial production. Economic losses associated with drought episodes are estimated to have increased globally by 3–7.5% per year since 2000. Floods impose similarly substantial costs. In Europe, floods caused average economic losses of around €6.5 billion per year between 1980 and 2023. The devastating floods in parts of Germany, Belgium and the Netherlands in July 2021 alone caused approximately €44 billion in damage (OECD, 2025; EAA, 2025).

Freshwater biodiversity can generate ecological portfolio effects, buffering environmental fluctuations and reducing risks to food supplies

and local economies. In Bristol Bay, Alaska, diversity among several hundred populations of sockeye salmon, reduces interannual variability in salmon returns. Without this diversity, fishery closures would occur about 10 times more frequently (Schindler et al., 2010). Similarly, an analysis of inland fisheries across 100 countries found that fish species richness was strongly associated with higher yields and, in Africa, reduced temporal variability in those yields (Brooks et al., 2016). This is of high relevance because freshwater fish are an important source of food and income for hundreds of millions people worldwide.

From competition to synergy

Efficiency gains alone will not reverse freshwater degradation unless they translate into lower environmental pressures and measurable ecosystem recovery.

Economic activities both drive competing water demands and offer opportunities to reconcile them. Key impediments include the under-rating of freshwater ecosystem services, the externalisation of environmental costs, and subsidies that encourage resource depletion. Conventional indicators of prosperity such as Gross Domestic Product (GDP) capture economic production without adequately accounting for

the depletion of the natural capital on which future prosperity depends.

A water-positive transformation therefore requires phasing out environmentally harmful incentives and redirecting financial flows away from damaging activities, while scaling up investments that strengthen freshwater biodiversity and ecosystem integrity. Similarly, technological innovation and improvements in water-use efficiency are insufficient if rising demand offsets efficiency gains. In high-consumption settings, efficiency and circularity must therefore be complemented by sufficiency to reduce avoidable and excessive water demand.

Protecting intact freshwater ecosystems is generally more effective, less costly and less uncertain than restoring them after degradation. Where freshwaters are already degraded, reducing environmental pressures and restoring ecosystem integrity are essential.

Recovery of freshwater biodiversity is possible when anthropogenic pressures are reduced. A time series from 22 European countries for the period from 1968 to 2020 revealed that taxonomic richness and abundance across 1,816 freshwater invertebrate taxa increased by an average of 0.7 and 1.2% per year, respectively. These improvements were associated with wastewater treatment and other environmental

management measures. However, recovery trends have largely levelled off since around 2010, and many rivers still fail to meet European ecological quality standards (Haase et al., 2025). These findings demonstrate both the effectiveness of past interventions and the need to address persistent and emerging pressures, including chemical pollution, invasive species, expanding hydropower infrastructure and river engineering.

Europe also illustrates the continuing scale of the freshwater predicament. According to the 2026 IUCN European Red List, 42% of Europe's 558 native freshwater fish species are threatened with extinction and a further 18% are classified as "near threatened." At the same time, water abstraction in EU countries declined by 19% between 2000 and 2022, demonstrating that water withdrawals can be reduced. However, water stress still affects around 30% of EU territory and 34% of its population. The challenge is to translate efficiency gains and lower water demand into reduced withdrawals and environmental pressures, particularly during critical periods, ultimately enabling measurable biodiversity and ecosystem recovery (Ford et al., 2026; EAA, 2026).

Substantial opportunities for synergy arise where ecological, social and economic objectives reinforce one another. Freshwater protection and restoration can simultaneously support

biodiversity, water security and climate change mitigation and adaptation. In particular, reconnecting rivers with their floodplains and wetland restoration can reduce flood and drought risks and associated economic losses, enhance carbon storage and provide habitats and refugia for freshwater organisms. Dynamic environmental flow rules can improve water allocation compared with rigid minimum flows while mitigating ecological impacts of river regulation. Improving water quality benefits biodiversity, public health and downstream water users.

Integrating nature-based solutions can deliver multiple ecological and economic benefits

Combining nature-based and engineered solutions, adapting infrastructure operations and, where appropriate, removing obsolete structures can generate ecological and economic benefits. For example, hydropower operations mimicking natural flow and temperature regimes can reduce downstream ecological impacts. Given the range of alternatives, investment decisions should compare nature-based, engineered and hybrid solutions over their full life cycles, including benefits from avoided damage, ecosystem services and long-term resilience. Although returns vary substantially across ecosystems and measures taken, the European

Commission estimates that nature restoration can generate €4–38 in benefits for each €1 invested (EU Directorate 2025; Van Zanten et al., 2023).

Not all competing demands can be reconciled through “win–win” solutions. Important trade-offs remain between irrigation and environmental flows, hydropower generation and river connectivity, and agricultural land use and floodplain restoration. However, changes in crop selection and diets, precision irrigation, alternative energy technologies and integrated land-use planning can reduce these conflicts. The overarching objectives are to maximise synergies, make unavoidable trade-offs explicit and prevent environmental and economic costs from being displaced across sectors, catchments, countries or generations.

From global commitments to measurable ecological outcomes

An evolving international policy framework provides opportunities to translate these principles into action. Under the Kunming–Montreal Global Biodiversity Framework (2022), countries agreed that at least 30% of degraded terrestrial, inland-water, coastal and marine ecosystems globally should be under effective restoration by 2030, and at least 30% of terrestrial, inland-water, coastal and marine areas should

be effectively conserved and managed. The Freshwater Challenge, supported by 54 countries and the European Union, aims to restore 300,000 km of degraded rivers and 350 million hectares of degraded wetlands by 2030 (UNEP, 2022)(Freshwater Challenge, 2026).

The EU Nature Restoration Regulation requires restoration measures covering at least 20% of the EU’s land and sea areas by 2030 and includes a target to restore at least 25,000 km of rivers to a free-flowing state. Corporate responsibilities are also becoming more prominent. EU sustainability reporting and due-diligence frameworks establish requirements for certain companies to identify, address and disclose material environmental impacts, risks and opportunities across their operations and value chains (Regulation EU, 2024). This includes impacts related to water and biodiversity. The decisive challenge is to translate these commitments into effective implementation, sustained investment and measurable ecological outcomes. The following nine priorities provide an integrated framework for action.

Nine priorities for action are proposed

Nine priorities ([Box 2](#)) are proposed to provide an integrated framework for moving from competition over freshwater towards synergies

between biodiversity conservation, human well-being and economic prosperity. They bring together the protection and restoration of freshwater ecosystems with technological innovation, effective governance, international cooperation and economic transformation. Together, they outline a pathway towards a water-positive future in which freshwater biodiversity and ecosystem integrity underpin water security, societal resilience and long-term prosperity for people.

Box 2: Nine priorities for action

Nine priorities for action provide an integrated framework for moving from competition over freshwater towards synergies between biodiversity conservation, human well-being and economic prosperity. They bring together the protection and restoration of freshwater ecosystems with technological innovation, effective governance, international cooperation and economic transformation. Together, they outline a pathway towards a water-positive future in which freshwater biodiversity and ecosystem integrity underpin water security, societal resilience and long-term prosperity.

1.

Recognise the hydrological cycle and freshwater ecosystems as global common goods and natural capital

2.

Prioritise nature-based and hybrid solutions alongside damage-minimising technical innovations

3.

Make water diplomacy an instrument for cooperation, stability and shared prosperity

4.

Safeguard biocultural diversity while preparing for ecological novelty

5.

Integrate water governance across the biodiversity, climate, food, energy and health sectors

6.

Harness AI for freshwater stewardship while curbing AI's water footprint

7.

Build a globally coordinated, near-real-time freshwater observatory

8.

Create the economic and financial conditions ensuring a water-positive transformation

9.

Establish a Blueprint for Freshwater Life: Prioritise protection, enhance restoration

1.

Recognise the hydrological cycle and freshwater ecosystems as global common goods and natural capital

The first priority is to govern water within hydrological and ecological limits and recognise intact freshwater ecosystems and their biodiversity as critical natural capital that underpins human well-being, economic prosperity and ecosystem services. Treating the hydrological cycle and freshwater ecosystems as global common goods emphasises their interconnectedness across political and geographic boundaries and the shared responsibility to safeguard their integrity and capacity to resist, and recover from, anthropogenic impacts (Mazzucato et al. 2025). At the global level, an Intergovernmental Panel on Water (IPW) could provide regular, independent scientific assessments of the state and trajectories of the global water cycle, freshwater resources, biodiversity and ecosystems, along with the associated risks and opportunities and options for action, thereby providing an evidence-based and internationally recognised foundation for coordinated actions.

2.

Prioritise nature-based and hybrid solutions alongside damage-minimising technical innovations

Investment decisions should be systematically based on comparisons of natural, engineered and hybrid alternatives over the full life cycle of infrastructure (Van Zanten et al. 2023; Browder et al., 2019). Rewetting wetlands, reconnecting floodplains and retaining water in landscapes can simultaneously contribute to water security, biodiversity conservation, carbon storage and disaster-risk reduction. Consequently, freshwater protection and restoration should be recognised as integral components of climate change mitigation and adaptation, rather than being treated solely as a matter of biodiversity and environmental policy. Given society's heavy reliance on technical water infrastructure, the objective is not to replace such infrastructure, but to foster innovation in the direction of smart combinations of nature-based and engineered solutions that maximise long-term ecological, social and economic benefits.

3.

Make water diplomacy an instrument for cooperation, stability and shared prosperity

Transboundary river basins account for around 60% of global freshwater flows, and 153 countries share transboundary rivers, lakes or aquifers. Yet, only 43 of these countries have operational cooperation arrangements covering at least 90% of their transboundary basin area (UNESCO & UNECE, 2024). To foster synergies and avoid inefficient resource use, water diplomacy needs to move beyond negotiating water volumes towards cooperation based on the principle of sharing benefits, risks, information and responsibilities across entire basins. Such cooperation is best supported by strong and independent transboundary institutions with basin-wide mandates for freshwater monitoring, conservation and restoration planning and implementation, contingency planning, transparent data management and exchange, and policy advice. The establishment and empowerment of such institutions is also an important step towards acknowledging and strengthening the status of freshwater and related ecosystems as a global common good.

4.

Safeguard biocultural diversity while preparing for ecological novelty

Freshwater ecosystems sustain cultural identities, knowledge, livelihoods and a sense of place, as well as biodiversity and ecosystem processes and services. The goal of conservation is to protect these ecological and cultural values and relationships beyond just economic values, while recognising that land-use change, climate change, altered flow regimes, pollution, biological invasions and other pressures are increasingly giving rise to novel ecological communities and ecosystems without historical analogues. Where historical ecological conditions cannot be restored, biodiversity and ecosystem management should focus on safeguarding ecological and cultural functions, evolutionary potential and resilient relationships between people and freshwater ecosystems.

5.

Integrate water governance across the biodiversity, climate, food, energy and health sectors

Water connects biodiversity, climate, food, energy and health. If poorly coordinated, policies and interventions can shift costs and risks between these sectors. Adopting an integrated approach to the water nexus means maximising synergies while minimising trade-offs across these interconnected systems. For example, hydropower supports climate mitigation but may increase river fragmentation and biodiversity loss. Conversely, nature-based solutions, including peatland rewetting, floodplain restoration and environmental flow protection, can simultaneously enhance biodiversity, water retention, climate change mitigation and resilience to droughts and floods. Sustainable food systems, building on plant-rich diets and reduced food waste alleviate pressures on freshwater resources and ecosystems. The top priority is to align policies, investments and management decisions at the river-basin scale, ensuring that decisions across sectors promote lasting synergies rather than reinforce competing demands, while delivering measurable ecological, economic and human health benefits.

6.

Harness AI for freshwater stewardship while curbing AI's water footprint

Artificial intelligence (AI) offers numerous new opportunities to improve freshwater monitoring, conservation and management, from biodiversity assessments and drought and flood forecasting to more efficient irrigation, reservoir operations and wastewater treatment. AI-supported irrigation, for example, has been associated with water savings of 30–50% and crop yield increases of 20–30%, although outcomes vary considerably across contexts and technologies. However, efficiency gains will only translate into lasting water savings if overall water withdrawals are effectively constrained. At the same time, the growing water footprint of AI is likely to be substantial and growing, with global water withdrawals projected to reach 4.2–6.6 km³ annually by 2027 (Li et al., 2025), including indirect water use associated with electricity generation. The top priority is to harness AI's potential for freshwater stewardship while minimising its environmental footprint through water- and energy-efficient computing, responsible data centre siting, water-efficient cooling technologies and transparent reporting of direct and indirect water withdrawals and consumption.

7.

Build a globally coordinated, near-real-time freshwater observatory

Advances in Earth observation, automated *in situ* sensors, environmental DNA (eDNA), drones, AI and process-based modelling offer unprecedented opportunities to monitor freshwater resources, ecosystem integrity and biodiversity at high spatial and temporal resolution. These technologies can expand monitoring coverage, improve cost-effectiveness and strengthen early-warning and forecasting capabilities. However, technological innovation must complement, rather than replace, long-term field observations, which remain indispensable for validation, detecting long-term trends and understanding ecological change. Building on existing initiatives, including the Freshwater Biodiversity Observation Network (FW BON), the National Ecological Observatory Network (NEON) and long-term ecological research (LTER) networks, the priority is to establish a globally coordinated freshwater observatory integrating innovative technologies, harmonised monitoring standards, interoperable data systems and open data sharing. Such an observatory would spur comprehensive assessments of freshwater ecosystem change, evaluations of conservation and restoration effectiveness, identification of emerging risks, and evidence-based policy and investment decisions.

8.

Create the economic and financial conditions ensuring a water-positive transformation

The transition towards a water-positive economy requires a fundamental shift in economic incentives, investment conditions and funding streams. Investing in conservation and restoration is insufficient if economic and financial systems continue to incentivise environmental degradation. Economic policy must therefore pursue a dual approach: phasing out environmentally harmful subsidies and activities while scaling up nature-positive investments and business models. This requires stable, predictable long-term policy frameworks, appropriate pricing of natural resource use and close coordination between governments and the financial sector. Financial institutions should systematically integrate freshwater-related dependencies, impacts and risks into investment, lending and risk-management decisions. However, because many investments in biodiversity and ecosystem integrity generate substantial societal benefits but insufficient private financial returns, public finance remains essential to support public goods and mobilise private capital, including through guarantees, concessional finance, blended finance and other risk-sharing instruments.

9.

Establish a Blueprint for Freshwater Life: Prioritise protection, enhance by restoration

The first priority of a global Blueprint for Freshwater Life must be to protect freshwater ecosystems that remain largely intact, including free-flowing rivers, near-natural lakes, wetlands and groundwater systems. Prevention is generally more effective and less costly than reversing ecological degradation, particularly given the time lags and uncertainties associated with restoration. Where ecosystems are degraded, reducing environmental pressures and restoring habitat conditions are essential to support biodiversity recovery and ecosystem integrity. The Blueprint should focus on six priority actions: ensuring high water quality, maintaining adequate water quantity, restoring ecological connectivity and natural dynamics, protecting and restoring critical habitats, conserving native freshwater species, and preventing and controlling invasive species. A Synthesis Centre for Freshwater Life, potentially integrated into the proposed global freshwater observatory, could coordinate scientific expertise, synthesise knowledge and translate evidence into effective conservation and restoration actions worldwide.

The choice ahead

Continuing along current trajectories will further disrupt the global water cycle, accelerate freshwater biodiversity loss and increase the risk of irreversible damage to ecosystem integrity and services.

The evidence is clear: freshwater biodiversity and ecosystem integrity are not competing demands on water resources, but essential foundations of water security, human well-being and economic resilience. Expanding water supply and improving efficiency alone cannot secure these benefits without addressing the underlying drivers of ecosystem degradation. The alternative is a water-positive transformation that protects intact freshwater ecosystems, reduces environmental pressures, restores degraded freshwaters and aligns economic incentives and investments with ecological limits.

The scientific knowledge, technological capabilities and policy frameworks to initiate this transformation already exist. What is needed now is sustained political commitment, institutional cooperation and a fundamental shift in economic incentives and funding streams to translate knowledge and commitments into tangible ecological and societal outcomes. The choice is not between water for people and water for nature. It is between continued depletion of freshwater natural capital and a future that safeguards the ecological foundations of water security, human well-being and economic prosperity.

References

- Bernhardt, E. S., E. J. Rosi, & M. O. Gessner. (2017). Synthetic chemicals as agents of global change. *Frontiers in Ecology and the Environment* 15(2), 84-90. <https://doi.org/10.1002/fee.1450>
- Bolt, & van Zanden. (2026). *Gross Domestic Product (GDP)*. Our World in Data – Maddison Project Database 2023. <https://archive.ourworldindata.org/20260730-020804/grapher/gdp-maddison-project-database.html>
- Brooks, E. G. E., Holland, R. A., Darwall, W. R. T., & Eigenbrod, F. (2016). Global evidence of positive impacts of freshwater biodiversity on fishery yields. *Global Ecology and Biogeography*, 25(5), 553–562. <https://doi.org/10.1111/geb.12435>
- Browder, G., Ozment, S., Rehberger Bescos, I., Gartner, T., & Lange, G.-M. (2019). Integrating Green and Gray: Creating Next Generation Infrastructure. *World Resources Institute*. <https://doi.org/10.46830/wrirpt.18.00028>
- Convention on Wetlands. (2025). *Global Wetland Outlook 2025: Valuing, conserving, restoring and financing wetlands*. Convention on Wetlands. <https://doi.org/10.69556/GWO-2025-eng>
- Dasgupta, P. (2021). *The Economics of Biodiversity: The Dasgupta Review*. HM Treasury.
- Deinet, S. et al. (2024). *Living Planet Index technical supplement 2024*. <https://doi.org/10.17605/OSF.IO/6TE9H>
- Dethier, E. N., Renshaw, C. E., & Magilligan, F. J. (2022). Rapid changes to global river suspended sediment flux by humans. *Science*, 376(6600), 1447–1452. <https://doi.org/10.1126/science.abn7980>
- EEA (2026). *Europe's state of water 2024: The need for improved water resilience*. <https://www.eea.europa.eu/en/analysis/publications/europes-state-of-water-2024>
- EU Directorate for Environment. (2025). From local action to global impact: EU delivers on biodiversity ahead of CBD COP17. *News Article*. https://environment.ec.europa.eu/news/eu-delivering-biodiversity-ahead-cbd-cop17-2026-05-22_en
- EEA (2025). *Europe's environment 2025: 1.4 Water and climate impacts*. European Environment Agency (EEA), Denmark, Copenhagen.
- Ford, M., Adams, C., Amaral, S., Artaev, O., Bănăduc, D., Barbieri, R., Bean, C., Bravničar, J., Buj, I., Čaleta, M., Carosi, A., Denys, G., Didenko, A., Doadrio, I., Filipe, A. F., Freyhof, J., Golub, D., Kostov, V., Lorenzoni, M., ... Trottet, A. (2026). *Measuring the pulse of European biodiversity*. European Red List of Freshwater Fishes. <https://doi.org/10.2779/880135>
- Freshwater Challenge. (2026). *The Freshwater Challenge: The planet's largest freshwater ecosystem restoration and protection partnership*. The Freshwater Challenge. <https://www.freshwaterchallenge.org/>
- Gordon, L. J., Finlayson, C. M., & Falkenmark, M. (2010). Managing water in agriculture for food production and other ecosystem services. *Agricultural Water Management*, 97(4), 512–519. <https://doi.org/10.1016/j.agwat.2009.03.017>
- Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., ... Zarfl, C. (2019). Mapping the world's free-flowing rivers. *Nature*, 569(7755), 215–221. <https://doi.org/10.1038/s41586-019-1111-9>
- Haase, P., Cortés-Guzmán, D., He, F., Jupke, J. F., Mangadze, T., Pelicice, F. M., Palmer, M. A., Rolls, R. J., Schäfer, R. B., Welti, E. A. R., & Sinclair, J. S. (2025). Successes and failures of conservation actions to halt global river biodiversity loss. *Nature Reviews Biodiversity*, 1(2), 104–118. <https://doi.org/10.1038/s44358-024-00012-x>
- He, F., Zarfl, C., Bremerich, V., David, J. N. W., Hogan, Z., Kalinkat, G., Tockner, K., & Jähnig, S. C. (2019). The global decline of freshwater megafauna. *Global Change*

- Biology*, 25(11), 3883–3892. <https://doi.org/10.1111/gcb.14753>
- IHME. (2025). Global Burden of Disease (GBD) Institute for Health metrics and Evaluation (IHME), Hans Rosling Center for Population Health, University of Washington <https://www.healthdata.org/research-analysis/gbd>
- IKSR, CIPR, & ICBR. (2018). *Das Makrozoobenthos des Rheins 2018* (Nr. 276; Fachberichte). https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Fachberichte/DE/rp_De_0276.pdf
- IKSR, CIPR, & ICBR. (2021). Fische im Rhein 2018/2019 (Nr. 279; Fachberichte). https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Fachberichte/DE/rp_De_0279.pdf
- Jones, E., Qadir, M., Vliet, M. T. H., Smakhtin, V., & Kang, S.-M. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment*, 657, 1343–1356. <https://doi.org/10.1016/j.scitotenv.2018.12.076>
- Lehner, B., Beames, P., Mulligan, M., Zarfl, C., De Felice, L., Van Soesbergen, A., Thieme, M., Garcia De Leaniz, C., Anand, M., Belletti, B., Brauman, K. A., Januchowski-Hartley, S. R., Lyon, K., Mandle, L., Mazany-Wright, N., Messenger, M. L., Pavelsky, T., Pekel, J.-F., Wang, J., ... Higgins, J. (2024). The Global Dam Watch database of river barrier and reservoir information for large-scale applications. *Scientific Data*, 11(1), 1069. <https://doi.org/10.1038/s41597-024-03752-9>
- Li, P., Yang, J., Islam, M. A., & Ren, S. (2025). Making AI Less “Thirsty”. *Communications of the ACM*, 68(7), 54–61. <https://doi.org/10.1145/3724499>
- Loomis, B. D., Luthcke, S. B., & Sabaka, T. J. (2019). Regularization and error characterization of GRACE mascons. *Journal of Geodesy*, 93(9), 1381–1398. <https://doi.org/10.1007/s00190-019-01252-y>
- Mazzucato, M., Okonjo-Iweala, N., Rockström, J., & Shanmugaratnam, T. (2024). *The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good*. Global Commission on the Economics of Water, Paris, 219 pp.
- McDermid, S., Nocco, M., Lawston-Parker, P., Keune, J., Pokhrel, Y., Jain, M., Jägermeyr, J., Brocca, L., Massari, C., Jones, A. D., Vahmani, P., Thiery, W., Yao, Y., Bell, A., Chen, L., Dorigo, W., Hanasaki, N., Jasechko, S., Lo, M.-H., ... Yokohata, T. (2023). Irrigation in the Earth system. *Nature Reviews Earth & Environment*, 4(7), 435–453. <https://doi.org/10.1038/s43017-023-00438-5>
- OECD (2017). *OECD Environmental Performance Reviews: Korea 2017*, OECD Publishing, Paris, France. <http://dx.doi.org/10.1787/9789264268265-en>
- OECD. (1993). *OECD Core Set of Indicators for Environmental Performance Reviews* OECD Environment Monographs, General Distribution document OCDE/GD(93)179. [https://one.oecd.org/document/OCDE/GD\(93\)179/en/pdf](https://one.oecd.org/document/OCDE/GD(93)179/en/pdf)
- OECD. (2012). *OECD Environmental Performance Reviews: Germany 2012*. OECD. <https://doi.org/10.1787/9789264169302-en>
- OECD. (2023). *OECD Environmental Performance Reviews: Germany 2023*. OECD Publishing. <https://doi.org/10.1787/f26da7da-en>
- OECD. (2025). *Global Drought Outlook: Trends, Impacts and Policies to Adapt to a Drier World*. OECD Publishing. <https://doi.org/10.1787/d492583a-en>
- Pacific Institute. (2025). *Water Conflict Chronology*. <https://www.worldwater.org/water-conflict/>
- Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on Nature Restoration and Amending Regulation (EU) 2022/869 (Text with EEA Relevance), Law Nr. OJ L, 2024/1991, 29.7.2024, PE/74/2023/REV/1 (2024). ELI: <http://data.europa.eu/eli/reg/2024/1991/oj>
- Sayer, C. A., Fernando, E., Jimenez, R. R., Macfarlane, N. B. W., Rapacciuolo, G., Böhm, M., Brooks, T. M., Contreras-MacBeath, T., Cox, N. A., Harrison, I., Hoffmann, M., Jenkins, R., Smith, K. G., Vié, J.-C., Abbott, J. C., Allen, D. J., Allen, G. R., Barrios, V., Boudot, J.-P., ... Darwall, W. R. T. (2025). One-quarter of freshwater fauna threatened with extinction. *Nature*, 638(8049), 138–145. <https://doi.org/10.1038/s41586-024-08375-z>
- Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L. A., & Webster, M. S. (2010). Population diversity and the portfolio effect in an exploited species. *Nature*, 465(7298), 609–612. <https://doi.org/10.1038/nature09060>
- Sinclair, J. S., Welti, E. A. R., Altermatt, F., Álvarez-Cabria, M., Aroviita, J., Baker, N. J., Barešová, L., Barquín, J., Bonacina, L., Bonada, N., Cañedo-Argüelles, M., Csabai, Z., De Eyto, E., Dohet, A., Dörflinger, G., Eriksen, T. E., Evtimova, V., Feio, M. J., Ferréol, M., ... Haase, P. (2024). Multi-decadal improvements in the ecological quality of European rivers are not consistently reflected in biodiversity metrics. *Nature Ecology & Evolution*, 8(3), 430–441. <https://doi.org/10.1038/s41559-023-02305-4>
- Statistics Korea/Ministry of Climate, Energy and Environment, National Sewerage Information System. (2026). *Sewerage Statistics 2024*. National sewerage service coverage statistics.

- Statistics South Africa. (2017). *Community Survey 2016, Statistical Release P0301*.
Pretoria: Statistics South Africa (Statistical Release Nr. P0301).
- Statistics South Africa. (2024). Census 2022: The State of Basic Service Delivery in South Africa (Census 2022: basic services report Report 03-01-83).
- Strayer, & Dudgeon, D. (2010). Freshwater biodiversity conservation: Recent progress and future challenges. *Journal of the North American Benthological Society*, 29(1), 344–358. <https://doi.org/10.1899/08-171.1>
- The GlambIE Team, Treichler, D., Velicogna, I., Wouters, B., Zekollari, H., & Zheng, W. (2025). Community estimate of global glacier mass changes from 2000 to 2023. *Nature*, 639(8054), 382–388. <https://doi.org/10.1038/s41586-024-08545-z>
- UNEP. (2022). *Kunming-Montreal Global Biodiversity Framework*, Convention on Biological Diversity. <https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf>
- UNESCO & UNECE. (2024). *Progress on transboundary water cooperation: Mid-term status of SDG indicator 6.5.2, with a special focus on climate change*. UNESCO, Paris, France. <https://doi.org/10.54677/QMQX8780>
- UNESCO WWAP. (2025). *The United Nations World Water Development Report 2025 – Mountains and Glaciers: Water Towers*. UNESCO, Paris, France. <https://doi.org/10.54679/LHPJ5153>
- UNSD. (2026). Environment Statistics Database: population connected to wastewater treatment. United Nations Statistics Division (UNSD). <https://data.worldbank.org/indicator/SH.H2O.SMDW.ZS?locations=CG>
- Van Zanten, B. T., Gutierrez Goizueta, G., Brander, L. M., Gonzalez Reguero, B., Griffin, R., Macleod, K. K., Alves Beloqui, A. I., Midgley, A., Herrera Garcia, L. D., & Jongman, B. (2023). *Assessing the Benefits and Costs of Nature-Based Solutions for Climate Resilience: A Guideline for Project Developers*. World Bank, Washington, D. C., USA. <https://doi.org/10.1596/39811>
- Van Zanten, B. T., Gutierrez Goizueta, G., Brander, L. M., Gonzalez Reguero, B., Griffin, R., Macleod, K. K., Alves Beloqui, A. I., Midgley, A., Herrera Garcia, L. D., & Jongman, B. (2023). *Assessing the Benefits and Costs of Nature-Based Solutions for Climate Resilience: A Guideline for Project Developers*. World Bank. <https://doi.org/10.1596/39811>
- WaterGAP. (2026). *WaterGAP – The Global Freshwater Model*. <http://www.watergap.de/>
- WGMS. (2023). *Fluctuations of glaciers database*. World Glacier Monitoring Service (WGMS). <https://doi.org/10.5904/WGMS-FOG-2023-09>
- WHO/UNICEF/JMP. (2025). *People using safely managed sanitation services (% of population)*, Democratic Republic of the Congo. World Bank World Development Indicators.
- World Bank/AMCOW. (2011). *Water Supply and Sanitation in the Democratic Republic of Congo: Turning Finance into Services for 2015 and Beyond. An AMCOW Country Status Overview*.
- WMO. (2023). *State of the Global Climate 2022*. Meteorological Organization (WMO), United Nations.

UNIVERSITÄT
DUISBURG
ESSEN

Open-Minded

GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN



isoe Institute for
Social-Ecological
Research

UFZ HELMHOLTZ
Zentrum für Umweltforschung

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN



IGB
Leibniz Institute of Freshwater Ecology
and Inland Fisheries



MARTIN-LUTHER-UNIVERSITÄT
HALLE-WITTENBERG



SENCKENBERG
NATURE RESEARCH

