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FUTURE PATHWAYS TO RESTORE THE ECOLOGICAL QUALITY OF GLOBAL FRESHWATER ECOSYSTEMS

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Colophon

Future pathways to restore the ecological quality of global freshwater ecosystems

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Contents

Summary

The ecological quality and biodiversity of freshwater ecosystems is under great pressure and at risk of further deterioration and decline. Freshwater ecosystems are valuable both for their intrinsic value (biodiversity and ecological functioning) as for their contribution to people (ecosystem services), as elaborated in the UN Sustainable Development Goals (SDGs). In line with these goals, this study explores future pathways and solutions for the ecological quality of global freshwater ecosystems. To do so, we used plausible projections on climate change, population, economic growth, and consumption as a basis (i.e. the SSP2-RCP6.0 scenario) without more ambitious climate policy, which we worked out using a global modelling study ranging from 1970 to 2070. As such, we set up an ecology-based scenario, comprised of elements on land-use and river basin management that can be modelled at the global scale: sustainable agriculture (including mixed landscapes), riparian buffer zones, wetland restoration, reduced water use, hydropower dam restrictions, and urban wastewater treatment. Together they cover four of the six priority action points to restore freshwater biodiversity (Tickner et al. 2020). All included scenarios – the Low ambition pathway, the Moderate ambition pathway, the High ambition pathway, and the Business-as-usual scenario, respectively –were modelled by a chain of models comprising land-use, nutrient emissions, hydrology, energy (including hydropower), and biodiversity. Modelled indicators include effects on water quality, wetland area, free-flowing rivers, freshwater biodiversity intactness, harmful algal blooms, and fish habitat suitability.

Our results indicate that, globally averaged, the ecological quality and biodiversity of freshwater ecosystems will further deteriorate in the Business-as-usual scenario and will approximately stabilise at current values under the High ambition pathway. The latter may be expected, as the overall projected pressures from dams and nutrient emissions in the High ambition pathway do not differ much compared to today; the increases in pressures due to population increase and economic growth will only just be neutralised. There are, however, large geographical differences. In the boreal zone, the overall quality of freshwater ecosystems will remain good as the indicated pressures remain low. In current highly affected regions such as Europe, North America, and China, the High ambition pathway will lead to improvements. This is not the case in Southern Asia, however, while even further deterioration is expected in Africa and South America.

The measures in land-use, agriculture, and wetland restoration in the High ambition pathway will contribute considerably to the ecological improvements. There are still significant possibilities for wetland restoration, for example. The urban wastewater scenarios, however, will not lead to improvement in aquatic ecosystems as treatment does not develop at the same pace as sanitation measures. The restrictions on future hydropower will stabilise (but not improve) the current state of river flow alteration.

Alongside its positive effects for biodiversity (SDGs 14 and 15), the High ambition pathway will have positive synergies with sustainable agriculture, the availability of clean water for humans, climate resilience, and flood protection, and hence will contribute to SDGs 2, 3, 6, 11, 12, and 13. A trade-off is defined with respect to future energy production, though this remains dependent on model assumptions on other sustainable energy sources. The model projections are subject to uncertainties due to missing factors in the models, suboptimal links between models, and a coarse resolution. Some recommendations are given to improve future model studies.

1 Introduction

1.1 Aim of this study

This study aims to explore future pathways and solutions for the ecological quality of freshwater ecosystems globally, both for their intrinsic value (biodiversity and ecological functioning) as for their contribution to people (ecosystem services) and the UN Sustainable Development Goals (SDGs). We work out an ecology-based approach to river basins at the global scale, by means of a global modelling study ranging from 1970 up to 2070. We set up an ecology-based scenario made up of modellable elements on conservation, land use, water quality management, river dams, and water use, within the SSP2 and RCP6.0 projections on population, economic growth, consumption patterns, and climate change. The results of this study are used in the PBL report *The Geography of Future Water Challenges – Bending the trend* (PBL 2023), with the aim to analyse different pathways towards sustainable solutions for global water challenges within the boundaries of current economic and climate projections.

1.2 Water-related challenges

1.2.1 Ecological quality and biodiversity of freshwater ecosystems

It is widely documented that the extent and ecological quality and biodiversity of freshwater ecosystems (rivers, lakes, floodplains, and other wetlands) has dramatically decreased around the world due to high pressures (IPBES 2019; WWF 2021; Ramsar 2018; Dudgeon 2020; Deinet et al. 2020; Feio et al. 2023). The extent and quality of these ecosystems is only expected to decline further in the future (PBL 2018; Janse et al. 2015). In the most densely populated and/or economically developed regions such as Europe, the United States, India, China, Japan, and others, most of the decline has already occurred, while further decline is still expected in other regions, especially in tropical regions in sub-Saharan Africa, South America, and Asia.

The main pressures causing this decline include: loss of wetland areas (both inland and coastal); loss of landscape connectivity; river regulation, fragmentation and flow disturbance by dams; eutrophication and other pollution; overexploitation of natural resources (e.g. fisheries); and spread of invasive species (MEA 2005; Dudgeon et al. 2006; GBO-5 2020). Many of these problems are only exacerbated by climate change, leading to higher water temperatures, increased drought risks, and more extreme high and low flows. Even though the significance of the various pressures varies regionally and among water types, these pressures have led to a decline in the biodiversity of freshwater ecosystems (rivers, lakes, wetlands), even surpassing, on average, the decline in terrestrial ecosystems (Almond et al. 2020).

To bend the curve of freshwater biodiversity decline, Tickner et al. (2020) describe and recommend a Priority Action Plan with the following elements, in line with previous reviews, tackling the main pressures mentioned above (of which elements 1, 2, 3, and 6 are covered in this study; see next section):

1. Accelerate implementation of environmental flows (i.e. retain and restore the natural flow regime of rivers);
2. Improve water quality to sustain aquatic life (i.e. reduce pollution to protect flora and fauna);
3. Protect and restore critical habitats (i.e. specifically floodplain wetlands are mentioned here);
4. Manage exploitation of freshwater species and riverine aggregates (i.e. avoid over-exploitation of fish and other species, and reduce sand and gravel extraction);
5. Prevent and control invasive alien species in freshwater habitats;
6. Safeguard and restore freshwater connectivity (i.e. restore both longitudinal and lateral connections within river basins).

The 'action plan' comprises three approaches or phases:

1) Avoid/relieve the threats;
2) Reduce/minimise harmful impacts if unavoidable; and
3) Restore.

The action plan has been built upon and worked out by several authors (Van Rees et al. 2020; GBO-5 2020; IUCN 2020; Dickens 2023), stressing synergies with ecosystem services for people, the need to account for (water flow) relations in river catchments, and the need for systems thinking and integrated water management. It has also landed in recommendations for the CBD Global Biodiversity Framework (CBD 2022) as well as the EU Biodiversity Strategy (2020).

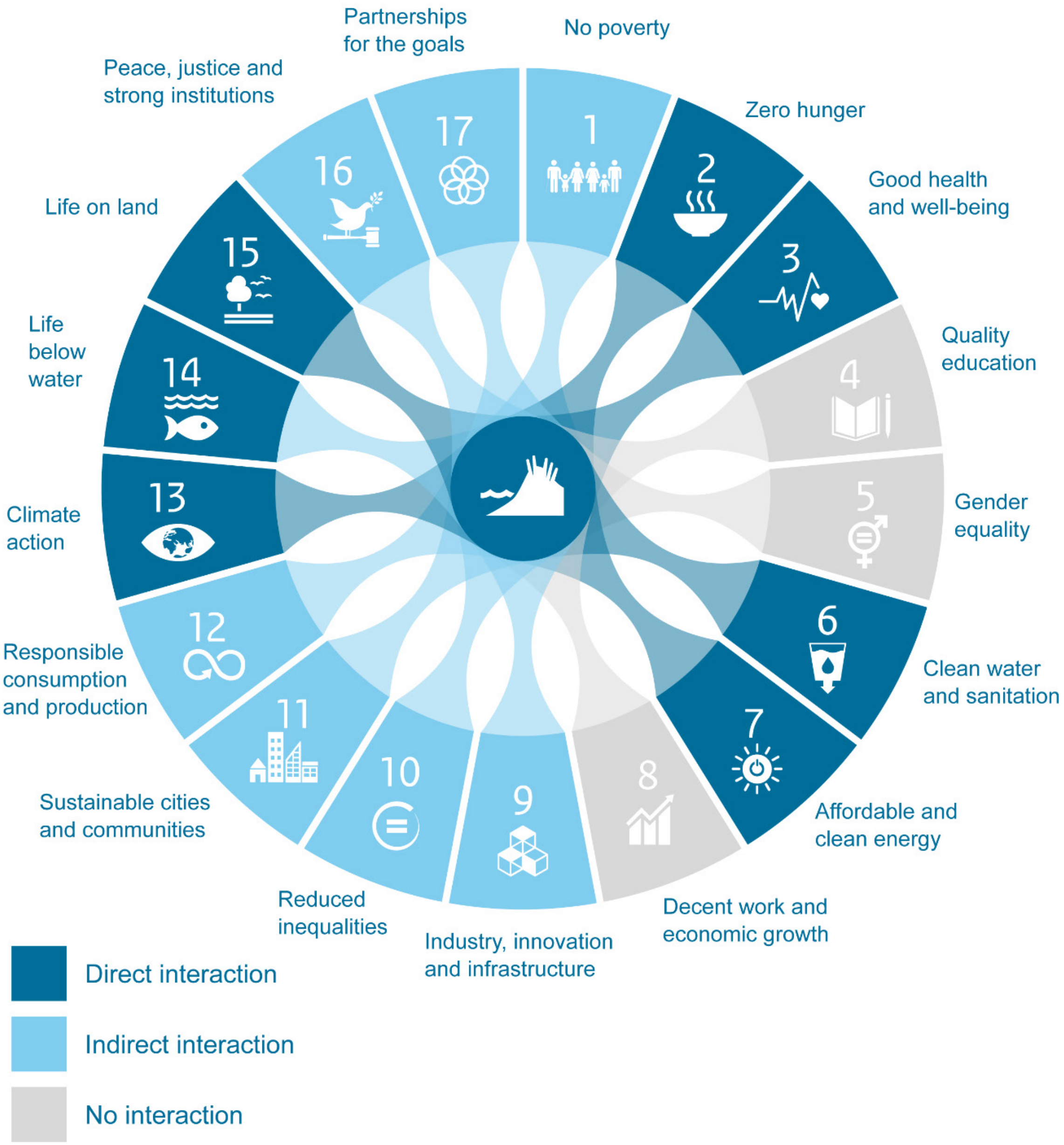
1.2.2 Human and climate water-related challenges

In parallel with the above, many global water-related challenges concern human interests (PBL 2018): adaptation to climate change, increasing risk of droughts (risk for food production), increased flood risk from seas and rivers, decreased sediment flow to the coastal zone, salinisation, sustainable energy security, deteriorating water quality, and threats to freshwater fisheries. Drought periods in dry regions cause the decline of wetlands, aggravate water shortages, and decrease natural water purification. The eutrophication of lakes causes toxic algal blooms imposing health risks, while the loss of coastal wetlands weakens coastal protection against rising sea levels. Moreover, coastal seas are threatened by increased nutrient loading, which increases the risk of harmful algal blooms and oxygen depletion in those waters and negatively affects biodiversity (e.g. coral reefs) and ecosystem services such as fisheries, aquaculture, and tourism. Indeed, many of these water-related problems come together and clash in growing cities. Ultimately, in the future, all these challenges will only increase, which can be summed up as too little, too much, or too dirty water.

There is an increasing awareness that the problems of freshwater biodiversity decline and the human water-related problems are interrelated (e.g. Boelee et al. 2017; UN-Water 2018). Essentially, most if not all water-related functions and services are based on well-functioning, resilient ecosystems, which each house their own particular biodiversity. A sustainable use of these resources, without compromising their future existence and ecological functioning, enables human societies to flourish and forms the basis for security and prosperity. This concept has been applied at a more general level as well, for both the UN Sustainable Development Goals (SDGs; UN 2015) (e.g. Naeem et al. 2015) as well as in the Nexus discussion (Hellegers et al. 2008; Hoff 2011). The system of SDGs is used as a framework to score scenarios – or pathways – on their ability to 'bend the trend' of the decreasing quality and resilience of river basins.

Several authors have analysed the relations between the biodiversity goals (SDGs 14 and 15) and the other development goals (e.g. SRC 2016; UN-Water, 2018; CBD, 2022; Wang et al., 2022). Direct positive links with aquatic ecosystem quality (included in SDG 15) are to be expected in the domains of Water quality (SDG 6), Human health (SDG 3), Sustainable food production (SDG 2), Climate resilience (SDG 13) and Life at sea (SDG 14), while trade-offs may exist with respect to Energy production (SDG7) and Land claims (SDG15). As is shown in Figure 1.1, secondary interactions occur with many other SDGs, which is further discussed in Chapter 5.

Figure 1.1
Interaction between sustainable development goals



1.3 Solution pathways

In the current era, water shortages are solved by building dams and water reservoirs as well as water relocation, water purification is solved by treatment plants, transport problems by altering river morphology, and flood protection is done in the form of dykes. These one-dimensional and technical solutions (so-called 'grey' solutions) are still the norm in tackling water challenges (Boelee et al. 2017; UN-Water 2015, 2018). Yet, as mentioned above, these challenges are firmly interrelated, and consequently there is a growing awareness that these technical solutions have, in many cases, reached their limits, or they have led to solutions for one issue while forgetting others and overlooking the broader scale (Boelee et al. 2017; UN-Water, 2018). This is even more important in view of current and projected climate change, which creates the need to 'move with nature' rather than fighting against it. More resilient and climate-proof solutions, with multiple co-benefits, can be found by adopting a 'green' approach in which the natural ecosystems themselves help to solve these problems ('ecosystem-based' or 'nature-based solutions' (NBS)). Concepts such as 'Living Rivers', Valuing Rivers', 'Room for the River', 'Ecological flow', 'Nature-based solutions' and 'Integrated water/catchment management' are examples of this much more integrated ecosystem-based approach as opposed to the more one-dimensional technical approaches, as is demonstrated in Figure 1.2.

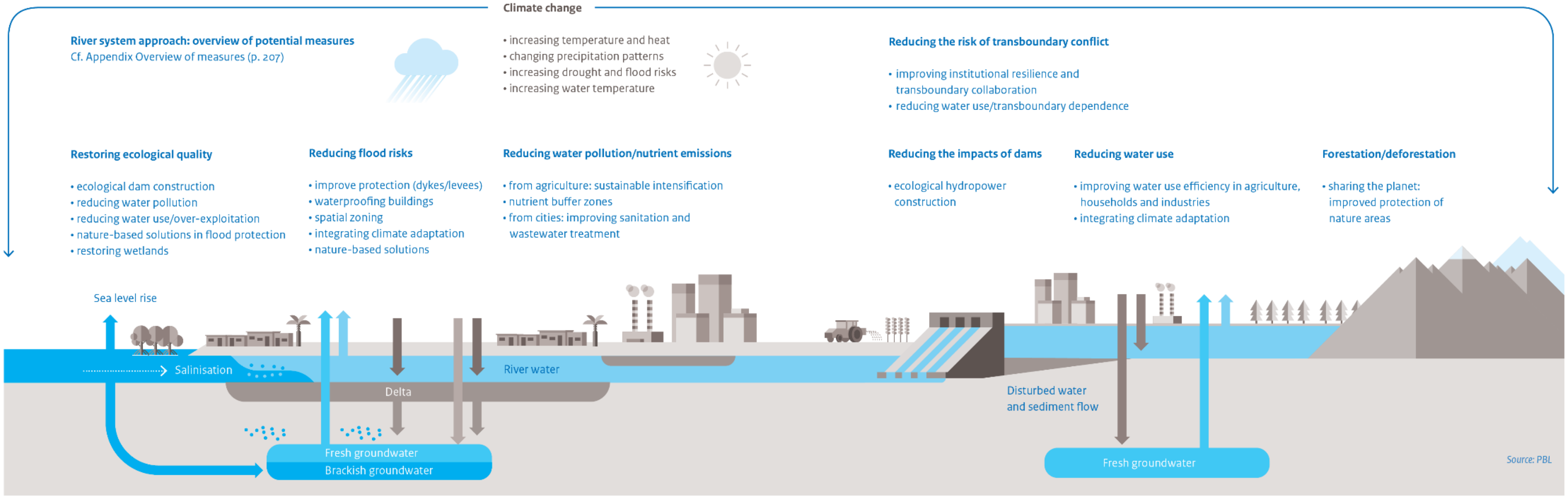
An optimally sustainable pathway combines a healthy planet with meeting the demands for food, water, energy, and safety for the future human population, as defined in the SDG framework. In this pathway, maximum coherence between these goals is ideal, particularly by protecting and sufficiently managing aquatic ecosystems to maximise their contribution to human well-being; in other words, carry a focus on nature-based solutions as far as possible. A common solution pathway (a) takes the carrying capacity and resilience of the global network of aquatic ecosystems as a starting point; (b) uses an ecology-based approach to meet global water needs, with catchments as a fundamental basis; (c) avoids trade-offs and diversion of problems to others; (d) builds on cooperation and creates synergies; and (e) minimises harmful effects to others in case of unavoidable choices. This approach may not be feasible everywhere, however; in those cases, technical and nature-based solutions can be combined to obtain an optimal compromise solution. The 2018 World Water Development Report (WWDR) worked out this approach to water management (UN-Water 2018). In Table 1.1 below, we summarise its main elements, particularly highlighting with an asterisk the ones important to and included in this study (for more details, see Appendix A).

Table 1.1
Summarised list of measures in an ecological approach to water management

Level	Measures
Watershed-level measures	Protection of carbon storage and/or water-retaining elements such as forests, organic soils, wetlands, and peatlands* Riparian buffer zones* Farming practices conserving organic matter and nutrients; mixed cropping systems*
River basin level measures	Restoration of floodplain wetlands* Nature-inclusive planning and design of hydropower plants* Smart water management to promote nutrient retention Sustainable fisheries Sustainable sand and gravel mining in rivers Species-oriented management (e.g. protection against alien invasive species)
Coastal zones	Restoration of coral reefs, mangroves and salt marshes
Cities	Wastewater treatment and recycling* Urban green and water bodies Artificial wetlands Green roofs
General measures	Increased water use efficiency* Reduction of carbon emissions to reduce climate change Societal and economic transitions

The measures denoted with an asterisk (*) are covered in this report and further developed in Chapter 2.

Figure 1.2
Ecosystem-based measures within a river basin explored in this report



1.4 Scope and restrictions of this study

As mentioned, in this study we aim to work out the ecological pathway (or High ambition pathway) from the water system perspective. This pathway is comprised of a combination of (a) land-use and catchment measures (based on 'Sharing the Planet' (SP) from Kok et al. 2023), and (b) direct water management-related measures, as listed in Table 1.2. We address both the extent to which the ecological and biodiversity goals will be met, as well as their relation to other water-related goals. We base our analysis on plausible climate change and population and economic projections (i.e. the SSP2-RCP6.0 scenario), implying a 3 to 4 degrees rise of global mean temperature at the end of the twenty-first century above pre-industrial values).

Table 1.2
Assumed biodiversity benefits of selected scenario components

Topic	Biodiversity benefits (1-6 from Tickner et al. 2020)
Sustainable agriculture, mixed landscapes	2 Water quality (3 Habitat protection)
Riparian buffer zones	2 Water quality 3 Habitat protection
Wetland restoration	3 Habitat protection 2 Water quality 6 Connectivity
Increased water use efficiency	1 Flow
Hydropower dam restrictions	1 Flow 6 Connectivity (2 Water quality)
Urban wastewater treatment	2 Water quality

These selected topics are just a subset of the more comprehensive list in Table 1.1. On the whole, this study is restricted to freshwater ecosystems, leaving out coastal and marine waters. Additionally, the measures analysed are confined to those in catchments (section 2.1) and in river systems (section 2.2). We restricted the study to elements that could be addressed by the available global-scale models. Measures in coastal systems and in cities (other than wastewater treatment) are covered in other FWC subprojects. Broader societal measures are also not included. We left out more ambitious climate change mitigation measures as well as structural economic and societal transitions. With respect to climate, the focus is primarily on adaptation.

We simulate the effects of an ecological scenario (called High ambition pathway) as well as two less ambitious scenarios (Low ambition pathway and Moderate ambition pathway) up to 2070 and compared these to past (1970) and recent (2015) data and to a Business-as-usual scenario. The scenarios are made up of different assumptions on the topics mentioned in Table 1.2. The Low ambition pathway assumes the adoption of mainly sectoral technological measures which are relatively simple to implement, the Moderate ambition pathway assumes further upscaling of these measures, and the High ambition pathway assumes a more integrated system approach including ecology-based measures as far as considered feasible, as facilitated by innovative governance. For all four scenarios, we evaluated their effect on the ecological and biodiversity goals for freshwater ecosystems. We did not touch upon the feasibility or other governance aspects of the scenarios, but these topics are addressed in the FWC Main report (Ligtvoet et al 2023a).

In Chapter 2, the scenario elements and assumptions are worked out, culminating in section 2.4 with an overview of the four modelled combinations/pathways. Chapter 3 describes the models included in the model chain and the way the scenarios were implemented. Chapter 4 then describes the indicators used for ecological quality and biodiversity (included in SDG15) and the model results, highlighting the large differences between the world's river basins. Finally, Chapter 5 covers, more qualitatively, the synergies and trade-offs of the ecological approach with the other water-related goals (water and food, flood risk management, water and energy, and others) and the societal and economical SDGs.

2 Elements of the pathways

In this chapter, the modelled options (inputs) are explained, divided in options at the land-use and catchment level and options at the water body level and urban measures, ending up with an overview of the model input for the four pathways: Business-as-usual scenario (SSP2/RCP6.0), High ambition pathway (all options combined), and two intermediate pathways called Low ambition pathway and Moderate ambition pathway.

2.1 Options at the land-use and catchment level

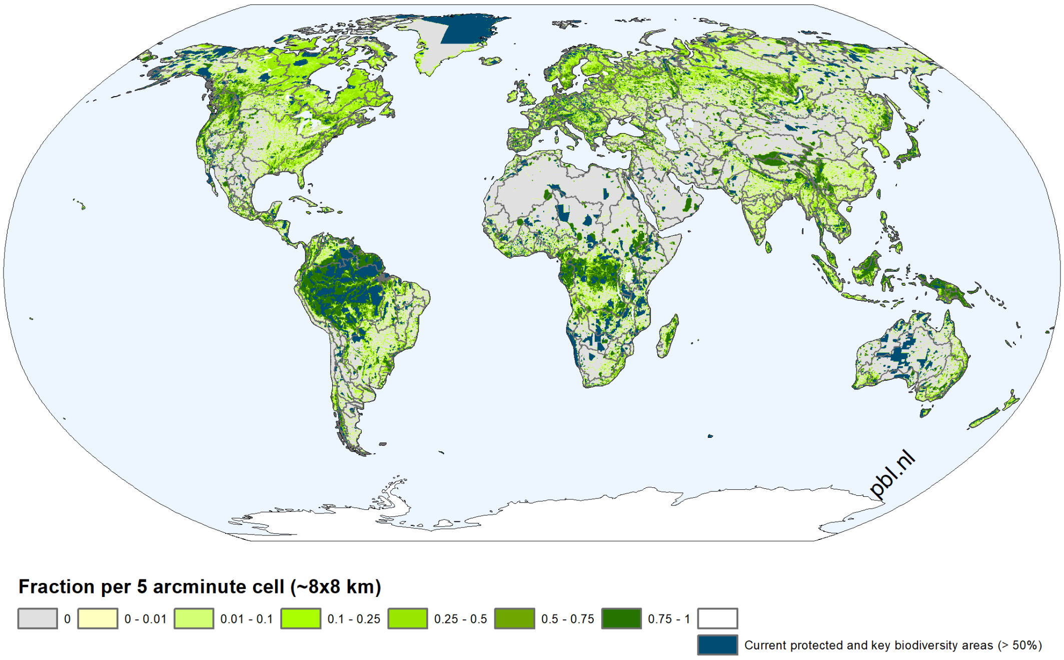
2.1.1 Land use pattern and nature conservation

As an alternative to the Business-as-usual SSP2 land-use scenario, we adopted the ‘Sharing the Planet, conservation only’ (SP_co) scenario, one of the four biodiversity scenarios developed at PBL by Immovilli and Kok (2021) and worked out by Kok et al. (2023). This scenario adopts a considerable increase in conservation areas and a transition towards more sustainable agricultural practices. It assumes, however, no change in consumption patterns, food waste, or climate policy compared to the ‘standard’ SSP2_RCP6.0.

In the Business-as-usual scenario, agricultural expansion and land-use patterns largely follow the projections by FAOs agricultural outlook (Doelman et al. 2018; Kok et al. 2023). Protected areas remain restricted to the Aichi target of 17% of the terrestrial area. Future land-use claims (simulated by the IMAGE model) are implemented at the cost of natural areas (forests, rangelands, wetlands) according to an allocation scheme per grid cell, based on suitability maps (Schipper et al. 2020).

The SP_co pathway, in contrast, assumes a trend towards mixed land-use systems of agriculture with nature (‘sharing’), by increased implementation of agroforestry in tropical biomes and mixed (70/30) cropland-nature patterns in temperate biomes. Sustainable intensification in agriculture supports increased crop production. Protected areas will (on top of the current protected areas) increase to 30% of the global terrestrial area, especially focussing on high carbon forests, peatlands, highland water retention areas (so-called ‘water towers’), riparian zones, and urban green spaces, to optimise ecosystem services delivered by these systems. Other wetland types, such as floodplain wetlands, are not specifically protected, however (see Kok et al. 2023; Immovilli and Kok 2021). As Figure 2.1 indicates, the extension of conservation areas is projected mainly in forest areas.

Figure 2.1
Conservation areas in SP scenario compared to current (from Kok et al. 2023)



Relative to now, the SSP2_RCP6.0 scenario projects an increase in agricultural land-use areas, especially in Africa and South America. In the SP_co scenario this increase is even somewhat higher, although less intensive and better integrated with nature. This is also reflected in decreased loss of nutrients.

2.1.2 Wetland protection

The significance of the protection and/or restoration of wetlands is twofold: (a) of to maintain the ecological values and high biodiversity of this rapidly declining ecosystem type (Davidson and Finlayson 2018), and (b) to safeguard the ecosystem services they offer, like water provision, retention of nutrients and other pollutants, carbon storage, flood risk reduction, fish production, and others (e.g. Ramsar 2020).

In addition to the SP_co land-use scenario, we applied a specific restoration policy for those wetlands (especially lowland wetlands) that were not effectively protected in the 'sharing the planet scenario' (SP). At the implementation of land-use claims, wetlands were excluded from conversion if other natural land cover types were still available in the grid cell. Only when these were used-up, the existing wetlands were converted. This contrasts with the other scenarios, in which all natural land cover types were converted proportionally. As basis for wetland locations, we used the Global Lakes and Wetlands Database (GLWD; Lehner and Döll 2005), which is mainly based on data from the 1990s. We applied the method to all wetland types defined in this map, either situated in river floodplains or outside. In the Business-as-usual scenario, as well as in the Low and Moderate ambition pathways, all land use types were assigned an equal chance of conversion.

As an alternative way to estimate the restoration potential of *floodplain* wetlands, we looked at the actual land-use in floodplains, defined as the zones around rivers which are inundated at least

1:1000 years. This was analysed by means of the Copernicus PROBA-V dataset (Buchhorn et al. 2020), available for 1992 and 2015 at 100 m resolution.

2.1.3 Agricultural nutrient management

Sustainable intensification in agriculture supports increased crop production, while minimising nutrient emissions to streams, rivers, and lakes. Sustainable agricultural systems require sustainable management of water resources and an efficient use of fertilisers.

We compared three levels of agricultural nutrient management: current practices ('SSP2'), 'sustainable practices' ('SSP1') and 'mixed cropping' (SP), in the order of decreasing emissions per area (details are described by Beusen et al. (2022)).

2.1.4 Reduction of water withdrawals

Global anthropogenic water withdrawals from rivers and lakes amount to approximately 4,000 km^3 per year, of which ~70% is used for agricultural purposes. In the Business-as-usual scenario, this is projected to increase to some degree. There are possible measures to reduce these withdrawals, which include rainwater harvesting, soil moisture conservation, and improved irrigation systems, which are all included in the High ambition pathway. If implemented together, LPJmL model calculations indicate that these measures decrease water withdrawals for irrigation by nearly 40% up to 2065. The feasibility of this reduction is questioned by some due to counteracting processes in irrigation practices (Grafton et al. 2018). Water withdrawal reductions can contribute to the integrity of river ecosystems by meeting 'environmental flow requirements' (Pastor et al. 2014), but the effect is dependent on the interplay of (future) hydrology, regional land-use, climate zones, climate change, seasonality, and other factors, thereby complicating future projections.

No assumptions were made on adapting crop types to changing conditions, such as possible shifts to more salt-tolerant crops in coastal areas or to drought-resistant crops in dryland regions.

2.2 Water and river management options

2.2.1 Protection and restoration of floodplain wetlands

The assumptions made on wetland protection described in the previous paragraph are also applied to floodplain wetlands.

2.2.2 Riparian buffer zones

Vegetated riparian buffer zones along rivers and streams are an important nature-based solution. If large enough and well-designed, they may even capture up to 85% of the nutrient losses by leaching from farmland before they could enter the water courses (Kao and Wu 2001; Braskerud 2002; Stutter et al. 2012; Hefting et al. 2013; Cole et al. 2020). Woody buffer zones may also reduce the water temperature of (smaller) streams, mitigating the effect of heat periods on fish and other aquatic organisms (Verdonschot et al. 2010). Additionally, they contribute to variation in stream morphology and sediments, thereby promoting biodiversity.

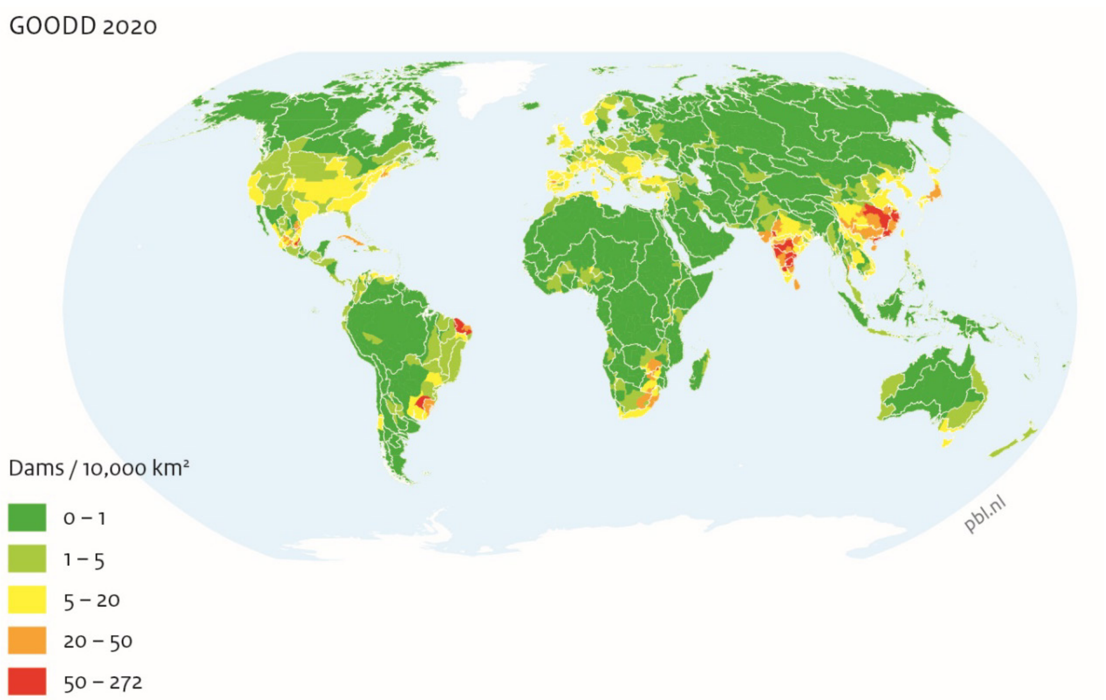
Estimates of the effectiveness of buffer zones for nutrient retention widely differ among studies, and are dependent on size (wideness), soil conditions, vegetation type (woody, grassy, shrubs, marsh), and many other factors (Cole et al. 2020). In general, a 30-metre wide buffer is an effective size. On the other hand, buffer zones are also criticised for being a temporary solution: their effectiveness may decline after some years as their nutrient (especially phosphorus) uptake capacity is fully used (Johnes et al. 2020). Arguably, in those cases, periodic management of the buffer zones will be necessary.

In the Moderate and High ambition pathways considered in this study, the preservation or restoration of riparian buffer zones is assumed along all river reaches flowing through agricultural areas. In the model implementation, this assumption is translated into a relative area (see chapter 3). It is assumed that they may capture 50% of the nitrogen and 80% of the phosphorus leached by surface and subsurface runoff. Deeper groundwater leaching is therefore assumed unaffected. These percentages are the average estimates of the mentioned review studies. Additionally, it is assumed that the uptake capacity is restricted to a maximum of 500 kg N/ha/y and 40 kg P, based on the maximum nutrient uptake capacity of riverine wetlands avoiding adverse impacts (Hefting et al. 2013).

2.2.3 Dams and reservoirs

River dams and reservoirs were built to deliver important services for humans, such as water storage and energy from hydropower (contributing to SDGs 2 and 11). According to the World Registry of Dams (WRD), the world now counts some 60,000 large dams, of which approximately 25% are (primarily) designed for hydropower production, about 50% for water storage, and the rest for other or mixed purposes (ICOLD 2009; Mulligan et al. 2021). As shown in Figure 2.2, nearly 40,000 of the existing dams have been geo-referenced (see the Global Georeferenced Database of Dams (GOODD); Mulligan et al. 2020).

Figure 2.2
Density of dams per water province, number of existing dams



Additional attributes are available for circa 7,300 of these dams (also contained in the GRaND (Lehner et al. 2011); Global Reservoir and Dam Database: Lehner et al. 2011) . The recently compiled

GeoDAR (Georeferenced Global Dams and Reservoirs) dataset (Wang et al. 2022) extends this number to about 25,000 dams.

Despite the benefits they provide, dams do destroy homes and land and are detrimental to other functions of rivers like sediment transport, water quality, biodiversity, and fisheries (harming SDGs 2, 6, 14, and 15). Dams obstruct fish migrations within the river system or between river and sea, and pose a threat to native species by altering water flow patterns and deteriorating water quality (e.g. Dudgeon 2010). New hydropower dams are being planned (e.g. Zarfl et al. 2015), while few rivers will remain free flowing. In this study we work out a number of global dam scenarios for hydropower, with the aim of finding a way to reach sustainable river management and minimising the trade-offs between these opposing goals. No scenarios were designed for dams for other purposes, such as water storage. All scenarios were calculated with the energy model TIMER (Gernaat et al. 2017; Gernaat et al. 2022). The chosen scenarios differ in the degree of ecological restrictions on dam locations, system type, size, and adaptation options.

- Allocation: ecological restrictions on location, e.g. protect currently free-flowing rivers
- Type and size: there are two types of hydropower plants: a dam with a reservoir, and a 'diversion canal plant', in which part of the river water is diverted through pipes (Gernaat et al. 2017). The latter system is much more environmentally- and socially friendly, but is less efficient in producing hydropower. A larger number of smaller plants and/or attractive renewable energy sources would therefore be required.
- Adaptation measures: where reservoirs are required, fish sideways or ladders, fish-friendly turbines, and ecologically-oriented water management could help reduce negative ecological impacts. Moreover, bypasses for sediment could reduce downstream erosion. However, some measures, particularly fish sideways, are only feasible for dams smaller than 20 metres (Van der Meer et al. 2021).

In this study, we defined the pathways as follows. The Low ambition pathway only includes adaptation measures, the Moderate ambition pathway includes set restrictions on locations and size, and the High ambition pathway only assumes diversion canal plants (i.e. without a dam and reservoir). A restoration or Maximum ambition pathway, with an algorithm for dam removal, was not designed for this study. The chosen options in the scenarios are summarised in Table 2.1 below.

Table 2.1
Options for hydropower in the different pathways

Scenario:	Business as usual 'Remain'	Low ambition pathway 'Adaptation'	Sharing the Planet scenario	Moderate ambition pathway 'Protection'	Half Earth scenario	High ambition pathway 'No increase'	Maximum Ambition pathway) ('Restoration')
None -> Technical-economic potential ***on top of existing*** (Gernaat et al. 2021)	+						
All new (and existing) dams with adaptation measures*		+		**+**		+	+
Exclude new dams in remaining Free-Flowing Rivers (Grill et al. 2019; Thieme et al. 2021)			+^	**+**	+~	+	+

Exclude dams >20m[@]	+		+	+
Exclude new dams, so only diversion canal power			+	
No increase in hydropower at all				+
Dam removal in 25% of the rivers		+		+

Note: the scenarios ' Sharing the Planet scenario', 'Half Earth scenario', and 'Maximum ambition pathway/Restoration scenario' were not used in this study but are included in the table for completeness and comparison with the earlier study by Kok et al. 2023.

[*] Management and adaptation measures are: fish sideways, fish-saving turbines, spillway design, optimise operational management, meet minimum flow requirements (30%) (Van der Meer et al. 2021). Adaptations to existing dams could not be implemented in the TIMER model, only to newly projected dams.
[@] Maximum dam height for practical feasibility of these adaptation measures.
[^] Actually: exclude new dams in the 30% protected areas in Sharing the Planet scenario (Kok et al. 2023)
[~] Actually: exclude new dams in the 50% protected areas in Half Earth scenario (Kok et al. 2023)

2.2.4 Sustainable aquaculture

In the SSP1 nutrient scenario, an efficiency increase is also assumed in the feeding of farmed fish in aquaculture, reducing per-unit nutrient losses by about 40% (Beusen et al. 2022).

2.3 Urban measures

2.3.1 Sewage connection and wastewater treatment

In this study, we used the different ambition levels on sewage connection and wastewater treatment described by Van Puijenbroek et al. (2022). Wastewater recycling (reuse) was not included in the modelled scenarios, though is an additional option. Likewise, other possible urban water management options such as increasing green spaces, increased rainwater retention, and improved storm water management were not included in the scenarios.

2.4 Selected options combined: four modelled pathways

This study assesses three combinations of the measures described in sections 2.1 - 2.3, combined in three scenarios, called Low ambition pathway, Moderate ambition pathway and High ambition pathway, alongside the Business-as-usual scenario. The Low ambition pathway only assumes minor changes in agricultural practices and emission reductions with respect to the Business-as-usual scenario; these are relatively easily applicable. In the Moderate ambition pathway, the point and non-point emissions are further reduced, and currently still free-flowing rivers are protected from new dams. In the High ambition pathway, the SP_co land-use scenario is adopted, together with restoration of wetlands and no new hydropower dams (see overview in Table 2.2).

These scenarios were implemented in the model chain (described in Chapter 3) and simulated from 1970 to 2070. The modelled output indicators and results are described in Chapter 4.

Table 2.2
Overview of measures simulated in the pathways. The numbers indicate the projected globally averaged changes between 2015 and 2070.

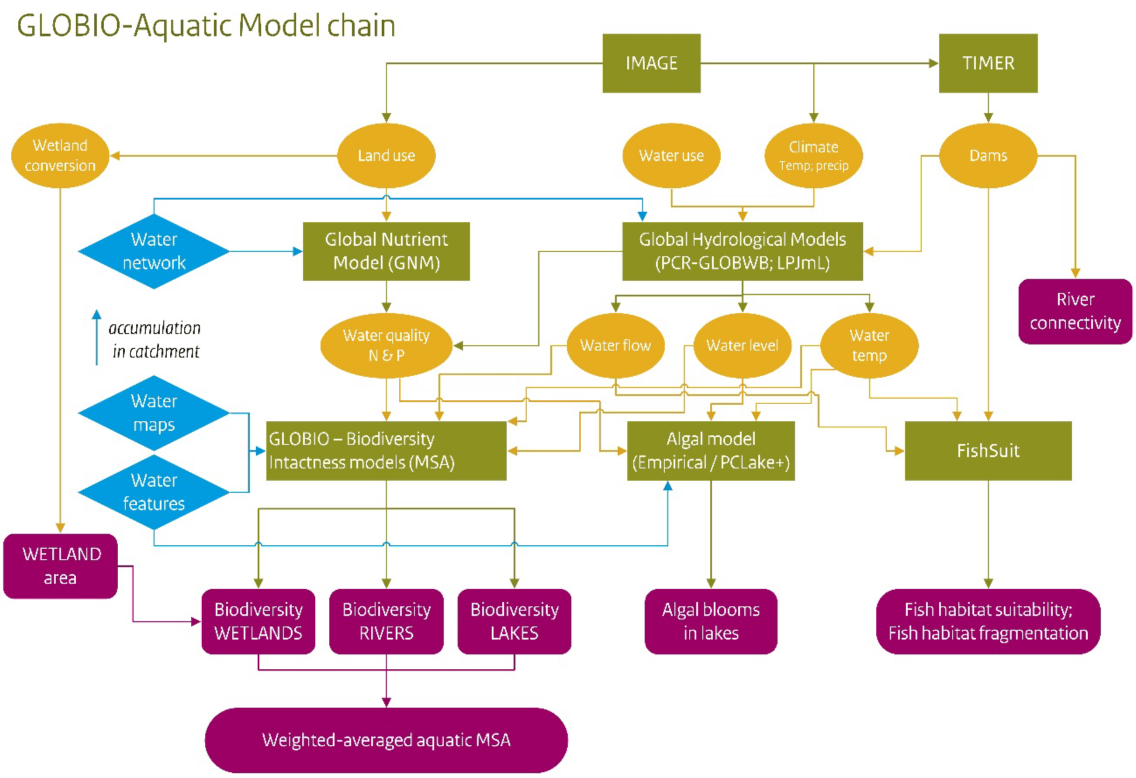
Measures (and effect)	Business as usual	Low ambition pathway	Moderate ambition pathway	High ambition pathway
Land use and agricultural practices	Current practices	More efficient nutrient use ('SSP1')	More efficient nutrient use ('SSP1')	Sustainable intensification ('Shared Planet', SP_co)
Wetland protection	No	No	No	Yes, if land-use claims met
EFFECT (see section 4.3): Change in wetland area	*-3%*	*-3%*	*-3%*	*+13%*
Riparian buffers	No	No	Yes	Yes
EFFECT*: Agricultural nutrient emissions	*+38%*	*+12%*	*+0%*	*-18%*
Urban water management: **-Sewage connection** **-Wastewater treatment**	('Low') 42% -> 58% 15% -> 28%	('Medium') 58% 39%	('Medium') 80% 50%	('High') 80% 51%
EFFECT** Urban nutrient emissions	*+48%*	*+45%*	*+25%*	*+25%*
COMBINED EFFECT *: Total nutrient emissions	*+28%*	*+12%*	*+7%*	*-11%*
Irrigation withdrawals	LPJ-Base (~current)	LPJ-Base (~current)	LPJ-High	LPJ-High
Hydropower:	Current practices	Limited adaptation	Protect free-flowing rivers	Diversion canal systems only
-Dams with reservoirs	+208	+208	+42	+0
-Diversion canal systems	+744	+744	+2031	+2124

** See Beusen et al. 2022. ** see Van Puijenbroek et al. 2023.*

3 Models and implementation

The scenarios in this study were simulated by the model chain, which is depicted in Figure 3.1 below. This chapter explains the different models and the way they were implemented. Land-use, climate and energy scenarios as modelled by IMAGE were taken up by global hydrological (PCR-GLOBWB and LPJmL) and nutrient (GNM) models to simulate water quality, flow, and temperature. The energy model TIMER was used for projections of hydropower dams. Based on these inputs, combined with the location and characteristics of water bodies, GLOBIO-Aquatic calculated the level of original aquatic biodiversity (MSA) for rivers, lakes, and wetlands. The average concentration of harmful algal blooms was also calculated. Moreover, the FishSuit model estimated the effects of climate change and dams on riverine fish species. All calculations were performed at a resolution of 30x30 arc minute grids (about 50x50 km at the equator).

Figure 3.1
Model chain for aquatic biodiversity. Models are depicted in green, variables in yellow, input maps in orange, water data input in blue, and output indicators in purple.



3.1 IMAGE and GLOBIO (terrestrial)

The land use scenarios SSP2 and SP_co were modelled by the IMAGE integrated assessment model (Stehfest et al. 2014) according to Van Vuuren et al. (2015) and Doelman et al. (2018). Based on this, land-use allocation was further refined by the terrestrial GLOBIO model as described by Schipper et al. (2020). IMAGE also includes a simplified climate model.

By including the wetland protection policy in the allocation rules, as mentioned in section 2.1.2, this policy was implemented in the High ambition pathway. Wetlands (if present in a grid cell) were

excluded from conversion due to (agricultural) land-use claims, if other non-wetlands natural land cover types were still available in that grid cell, until these were 'used-up'. In the default model configuration (as used in BaU), all natural land cover types are assumed equally susceptible (cf Van Asselen et al. 2013). These different assumptions have no effect on the total farmland area.
As the GLOBIO set-up does not allow dynamic simulations, separate runs were performed for every 'projection year', i.e. 1970, 2015, 2030, 2050, and 2070, in line with earlier GLOBIO applications.

3.2 TIMER

TIMER calculates the use of energy sources based on energy demand (according to the SSP2-RCP6.0 scenario), the available capacity of energy sources, assumed energy policy, and so-called cost-supply curves. The potential remaining hydropower capacity was derived from river flow data and other physical and economic constraints. In the scenarios, further ecological constraints were included as described in section 2.3. The model then calculates the required production capacity per energy source, including hydropower, and the preferred locations (within the constraints) as well as the type of plant: dam-with-reservoir or diversion canal system. Locations are chosen in order of cost-per-yield, applied per IMAGE region (for details see Gernaat et al. (2017) and Gernaat et al. (2022)).

3.3 Global Nutrient Model (GNM)

GNM (Beusen et al. 2015) was used to calculate the year-averaged total-N and total-P emissions and concentrations in the surface waters. Emissions are the sum of point sources (urban emissions) and diffuse sources, mainly agricultural, using land-use projections from IMAGE. Transport through the river system was calculated by combining the emission model with the global hydrological model PCR-GLOBWB (Sutanudjaja et al. 2018), using a grid approach with a 30 arc minutes resolution. The implementation of the different options for agricultural land-use and practices, such as nutrient use efficiency, is further described in Beusen et al. (2022).

3.4 Buffer zones

As the model resolution is too coarse to implement the exact allocation of riparian buffer zones, the option of buffer zones is translated into a fraction of the farmland area. The most detailed available land use maps, the 2015 Copernicus Global Land Service, 100m land cover map (Buchhorn et al. 2020), and the Global River Classification (GloRiC, Ouellet Dallaire et al. 2019), have been used to estimate the buffer area. The size of the buffer zones was determined by the resolution of the GLOBIO land-use map and equals those used in the Sharing the Planet scenario (Kok and Immovilli 2020; Kok et al. 2023). The GloRiC map discerns several size classes of rivers: 'large' (e.g. the Rhine), 'medium' (e.g. the Meuse, Moselle, Seine), 'small' (e.g. the Marne, Ruhr), and 'very small'. The buffer areas were chosen as 300 m around medium and large rivers and 150 m around small rivers; very small rivers are excluded (i.e. assumed to be included in the other ones). To determine the presence and size of buffer zones, for every 100x100 m raster cell the distance to the nearest river is calculated; if this distance is smaller than the above-mentioned threshold the cell is included in the buffer zone. Next, the agricultural area within these zones is calculated. The agricultural areas within buffer zones are then aggregated to a lower resolution, by calculating the area buffer zones within each 30 arc minutes grid cell. This procedure results in an average 1% of the agricultural area designated as buffer zone, albeit with large local variations. This is then used as an input to the global nutrient model (GNM: Beusen et al., 2022) by accounting for the nutrient uptake capacity of this area.

Scenarios for *urban emissions* are modelled as described in Van Puijenbroek et al. (2023); the global average results are included in Table 2.2.

3.5 Global hydrological models

As stated, runoff and river discharge from the model PCR-GLOBWB was used in combination with the GNM model for the calculation of water quality (nutrients). Included is the module DynWat for surface water temperatures (Wanders et al. 2019).

River flow was also modelled by LPJmL, as a function of (agricultural) water abstractions, climate, and dams. To reduce the number of model runs and data conversions, from the six scenarios simulated by LPJmL, we used the LPJmL Business-as-usual scenario for our Business as usual and Low ambition pathway simulations, and the LPJ 'current' (2015) data for our Moderate ambition pathway and High ambition pathway scenarios. We did not use the LPJ 'High' scenario to calculate the river flow deviation, as the LPJ results for this scenario seemed confusing, due to a combination of processes which needed further analysis.

3.6 GLOBIO-Aquatic

Aquatic biodiversity intactness (expressed as 'MSA', literally 'mean species abundance') was calculated by the GLOBIO-Aquatic model (Janse et al. 2015, 2016), for rivers, lakes, floodplains, and other wetlands. The MSA indicates to what extent the original species composition and abundance (i.e. in the undisturbed situation) is still present in the actual (disturbed) situation. Hence, MSA values vary between 1.0 (original species composition fully intact) and 0.0 (all original species lost). The model consists of a set of empirical relations based on a number of case studies (before-after-control-impact studies or comparative studies between disturbed and undisturbed waters). Like the terrestrial GLOBIO model, the indicator includes both the extent ('quantity') of natural ecosystems and their suitability for the natural biodiversity ('quality'). Some adaptations were made with respect to the 2015 model version (Janse et al. 2015):

a) Updated maps were used for lakes (based on the HydroLakes dataset (Messager et al. 2016) and rivers (based on the GRWL; Allen and Pavelsky 2018)). Lake characteristics like depth were now also derived from HydroLakes.
b) For MSA-rivers, equations were included for the dependence on nutrients, replacing the relation with upstream land-use area used in the earlier model version. This allows for a more differentiated evaluation of agricultural land-use intensity and other nutrient management options and is also in compliance with the MSA equations for lakes.
c) The model has been fully reprogrammed in Python.

The new nutrient equations for rivers are based on data of Poikane et al. (2019) and Phillips et al. (2018), who analysed an extensive dataset on the relations between nutrients (total nitrogen, TN and total phosphorus, TP) and the Ecological Quality Ratio (EQR) for European rivers for use in the European Water Framework Directive. The EQR is regarded as a good equivalent for MSA. They derived threshold TN and TP concentrations for EQR values of 0.6 (the lower value for 'Good' status) and 0.8 (the lower value for 'High' status), We used these median threshold values to derive logistic (S-shaped) functions between EQR and the ^{10}log of TP resp. TN. A logistic equation has been chosen, because of its 'smooth' boundaries and we follow the widely used log-transformation of concentrations. Of the two parameters in the logistic model, alpha should be interpreted as the log-concentration at the point of inflection and beta denotes the steepness of the curve (Figure 3.2).

We follow the general approach of separate functions for phosphorus and nitrogen (an alternative would be the use of multiple regression, but this was not yet possible due to limited data availability). The literature is ambiguous in how to combine both functions (or standards). All approaches are simplifications, as in reality the joint effect of both nutrients is a complicated issue, different for different processes and organisms and dependent on season. As the effects of the two substances are not independent (they exert their effect mainly jointly via stimulation of productivity), a simple multiplication does not hold, and taking the strictest one would overestimate the effect. One may argue (e.g. sustained by the study of Moss et al. 2005) that the nutrient with the relatively lowest concentration with respect to its threshold (i.e. with the lowest impact, or highest MSA) would be decisive; analogous to Liebig's law of the limiting nutrient for algal growth. Other studies, like Phillips et al. (2018), indicate a more 'intermediate' interaction between the two at intermediate concentrations, while the limiting nutrient concept still holds for more extreme cases. As a proxy for this we chose the *average* of the two functions. In GLOBIO, we implemented the option of choosing either the maximum or the mean function, both for rivers and for lakes. In this study the maximum remaining MSA was used.

The resulting equations (also depicted in Figure 3.2) are:

$$MSA_P = \frac{1}{1 + EXP[-\frac{(LOG(TP + 0.001) - \alpha_P)}{\beta_P}]}$$

with α_P = - 0.886; β_P = - 0.35; TP in mgP/L.

$$MSA_N = \frac{1}{1 + EXP[-\frac{(LOG(TN + 0.01) - \alpha_N)}{\beta_N}]}$$

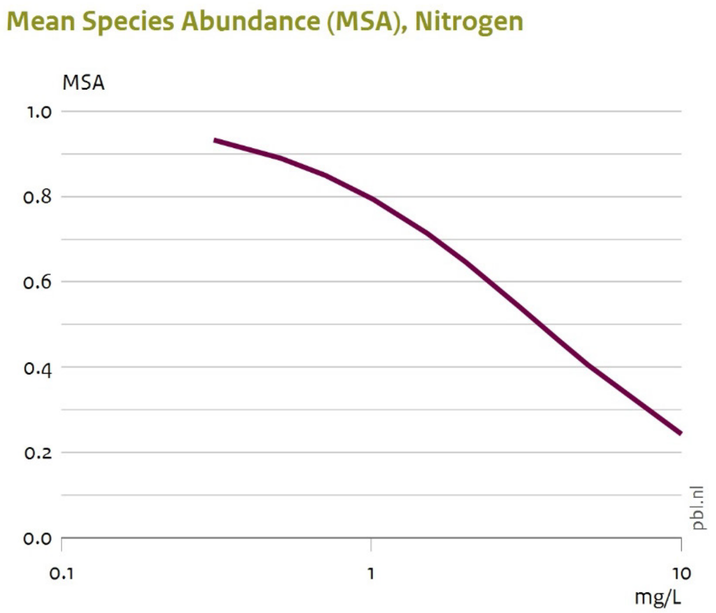
with α_N = 0.544; β_N = - 0.4; TN in mg N/L.

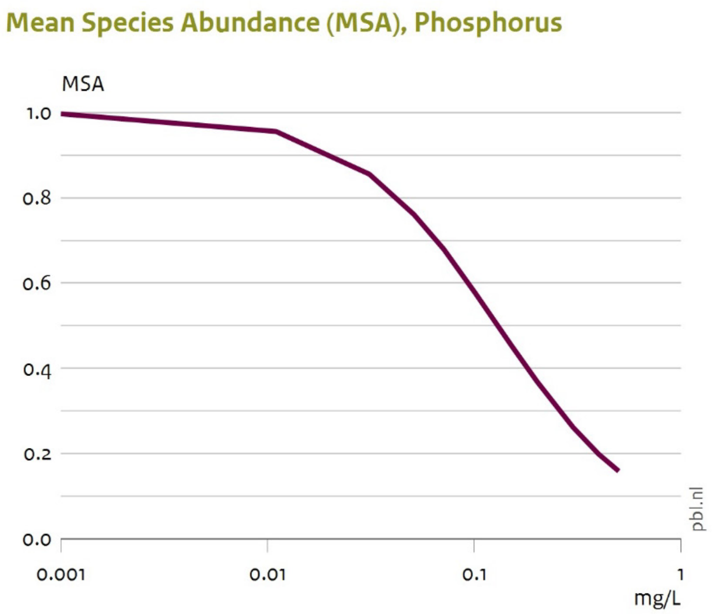
MSA_{Nut} = AVERAGE(MSA_P, MSA_N); or
MSA_{Nut} = MAX(MSA_P, MSA_N)

The thresholds for rivers are less well established than those for lakes and are still in development. This is due to differences in nutrient fractions used (e.g. NO_3 besides TN, or Soluble Reactive Phosphorus (SRP) besides TP), methodological differences, scarcity of data, missing countries, interaction with other stressors, and others.

A possible improvement would be to distinguish between the different (broad) river types (mainly based on size, altitude and alkalinity), but the present data are too scarce for that. Another follow-up is an update of the meta-analysis on case studies which is in progress, following the increased availability of literature data since the meta-analysis by Weijters et al. (2009), including nutrient data beyond land-use categories. The 'old' equation was kept in the model for comparison between versions.

Figure 3.2
MSA-Rivers as a function of nutrient concentrations, as used in the GLOBIO Aquatic model: total Nitrogen, total Phosphorus





All other GLOBIO-Aquatic modules are described in Janse et al. (2015) and Janse et al. (2016). The deviation from the natural flow pattern over the year (the so-called AAPFD) was used as a measure for hydrological disturbance. The module on dams is currently being extended and updated by integration of the data by Koppenjan (2018). A module for climate change (drought risk and temperature) is in development (Yellowlees 2020) but could not yet be used in this project.

Table 3.1 gives an overview of the model elements in GLOBIO-Aquatic as well as in FishSuit (described below).

Table 3.1
Drivers and indicators (per water type) included in GLOBIO-Aquatic and FishSuit.

Model and Indicator	**GLOBIO-Aquatic MSA**	**GLOBIO-Aquatic MSA**	**GLOBIO-Aquatic MSA**	**GLOBIO-Aquatic MSA**	**GLOBIO / PCLake+ Harmful algae**	**FishSuit Fish habitat suitability**
Water type Driver	Lakes	Rivers	Floodplain wetlands	Isolated Wetlands	Lakes, Reservoirs	Rivers
Conversion (area loss)			+	+		
Land-use in catchment			+			
Land-use in current pixel				+		
Accumulated nutrients (N,P)	+	+	o		+	
Nutrients (N,P) from current pixel				o		
Hydrological disturbance	o	+	+	o		+
Water temperature	o	o	o	o	+	+

Note: '+' denotes implemented modules, used in this study; 'o' are modules in development, not yet included.

As the drivers for MSA are assumed to be independent of each other, the final MSA value is obtained by multiplication of the applicable driver factors. For an overall aquatic MSA calculation, the values for the different water types were area-averaged over the region of interest (a pixel, river basin, or other).

3.7 Algal model

Harmful algal blooms (cyanobacteria) can be modelled by means of PCLake+ (Janssen et al., 2018; Janssen et al. 2019; Tigli et al. 2024). We used an empirical model (Hakanson et al. 2007) instead as a proxy (see Janse et al. 2015 or Janse et al. 2016), with TN, TP, and water temperature as input variables.

3.8 FishSuit

FishSuit is a model for habitat suitability and geographic range fragmentation of freshwater fish species; an extensive model description is given by Barbarossa et al. (2021). Future habitat suitability is based on climate niche envelopes drawn for the current distribution of fish species, following the approach of (a type of) species distribution models (SDMs) (Elith and Leathwick, 2009; Watling et al., 2013). Temperature and streamflow extremes are included as climate variables., The aggregated output indicator is the 'potentially affected fraction of species' (PAF), i.e. the fraction of species expected to lose a part of their habitat. This indicator differs from (and is complementary to) the biodiversity intactness (MSA) since the PAF is based on the distribution of specific (fish) species related to an environmental factor, while MSA measures change relative to the original species composition and abundance, based on a comparison of case studies. The fragmentation level is calculated as a connectivity index, based on the presence of river dams within the distribution area of fish species per catchment (Barbarossa et al. 2020). The model discerns diadromous and non-diadromous species. This indicator denotes a possible threat to the fish populations, but not necessarily an effect on their survival.

In this project, we used PAF simulations for 3.2 degrees rise in global mean air temperature (compared to the pre-industrial period, 1850-1900), which is on average (for different GCMs) reached in the 2070s in the RCP 6.0 scenario (Barbarossa et al. 2021). Distribution data of riverine fish species were used at a 5 arc minutes resolution and overlayed with the current and simulated weekly water temperature and flow to simulate range contractions as a function of water warming. This has been done for two different assumptions on the species' dispersal capabilities (none or maximum), i.e. whether the species would be able to migrate to other, suitable, habitats or not (Barbarossa et al. 2021). The analysis was restricted to riverine (lotic) species as the temperature model used does not account for stratification in lakes.

For fragmentation, we calculated the connectivity index for the FWC hydropower pathways (Table 2.1 and 2.2) using the same methodology reported in Barbarossa et al. (2020).

4 Effect of pathways on ecological indicators

In section 2.4 of this report, we described several scenarios: the High ambition, Moderate ambition, and Low ambition pathways as well as the Business-as-usual scenario. In this chapter, we discuss and report on the modelled impact of these scenarios on the following indicators: climate variables, water quality; wetland area; dams, river flow, and free-flowing rivers; biodiversity intactness (MSA); harmful algal blooms in lakes; and fish habitat suitability.

4.1 Climate variables (Business-as-usual scenario only)

4.1.1 Water temperature

Water temperatures in the top layer tend to follow those of the air above, with some lag time and dependencies on water morphometry, dynamics, and wind, to name a few. The RCP6.0 climate scenario projects an average 2.3 degrees air temperature rise in 2070 (based on the average of several GCMs; see ISIMIP 2b[1]). Regional surface water temperatures calculated by the DynWat model (Van Beek et al. 2015) were used by FishSuit to calculate the effects of climate change on fish species, as demonstrated in section 4.7. For application in the algal module (section 4.6), these same data were then used to calculate the average water temperatures in the phytoplankton growing season (i.e. the period of the year when temperature exceeds 9 degrees centigrade). No other climate scenarios were used apart from the Business-as-usual scenario.

4.1.2 Hydrological climate effects

Climatic factors such as precipitation surplus or deficit, in combination with land use, are expected to affect water retention, river flow, and the frequency of droughts.. The effects vary between river systems, however, as shown by the PCR-GLOBWB and LPJmL simulations.

4.2 Water quality and effect of buffer zones

The FWC-2 report on water quality (Beusen et al. 2015, Van Puijenbroek 2023) reported on water quality (N and P) as modelled by GNM. Their global results show that emissions will continue to increase in the Business-as-usual scenario, while only somewhat decreasing in the High ambition pathway, as demonstrated below in Figures 4.1 There are, however, significant differences between regions, with decreases projected in Europe, North America, and China, and increases projected in India and Africa in particular. The differences between the pathways indicate the positive impacts of the assumed measures. Differentiated by source, Figure 4.2 shows that the High ambition

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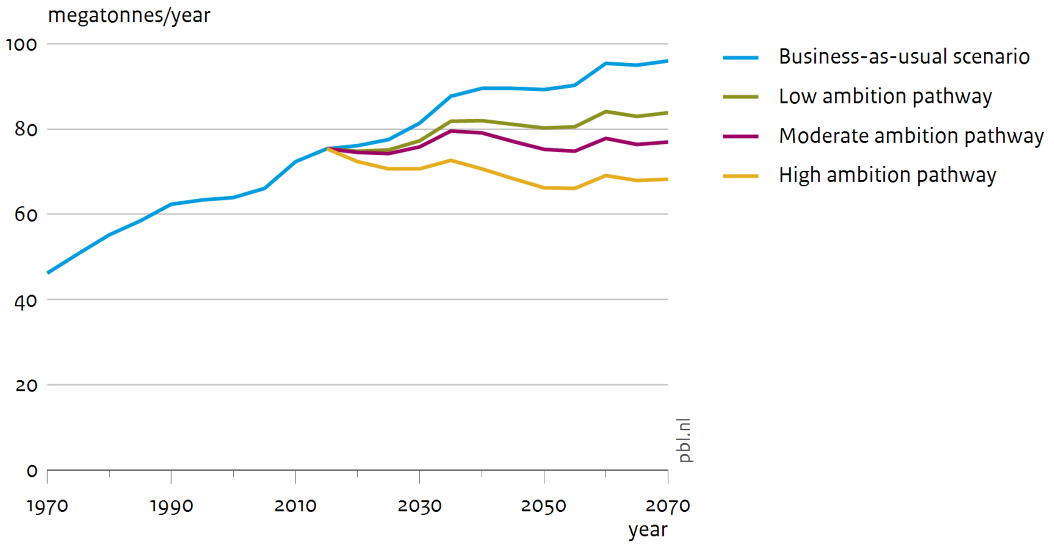
[1] www.isimip.org/protocol/2b [ISIMIP = Inter-sectoral Impact Model Intercomparison Project].

pathway leads to an overall decrease of the N (but not the P) emissions from agriculture, compared to 2020, whereas the urban P emissions decrease but the urban N emissions even increase. This shows that the assumed improvements in wastewater treatment cannot always keep up with the increased sewer connections.

Figure 4.1
Projected nutrient deliveries to rivers

Projected global nitrogen delivery to rivers under different pathways



Projected global phosphorus delivery to rivers under different pathways

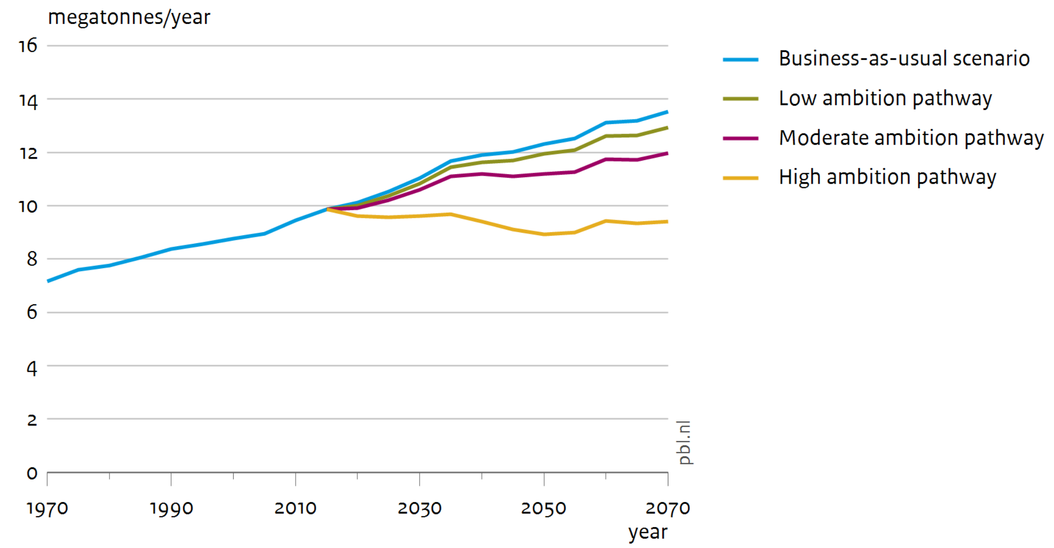
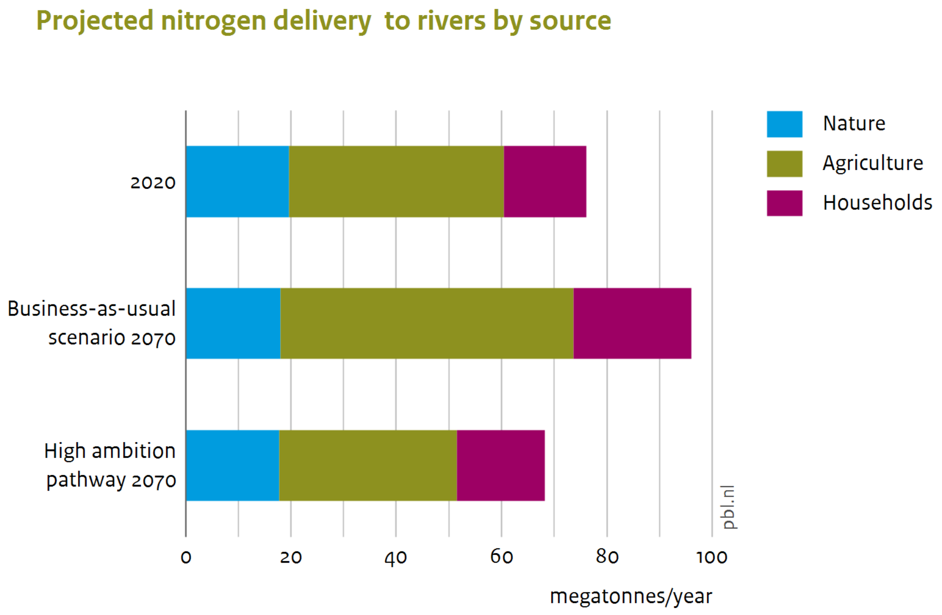
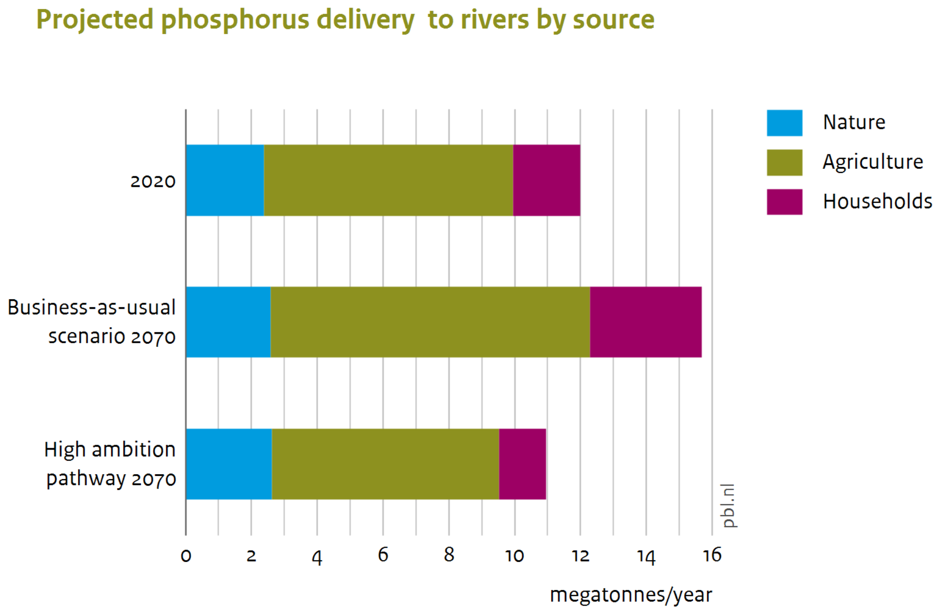


Figure 4.2
Projected nutrient deliveries by source





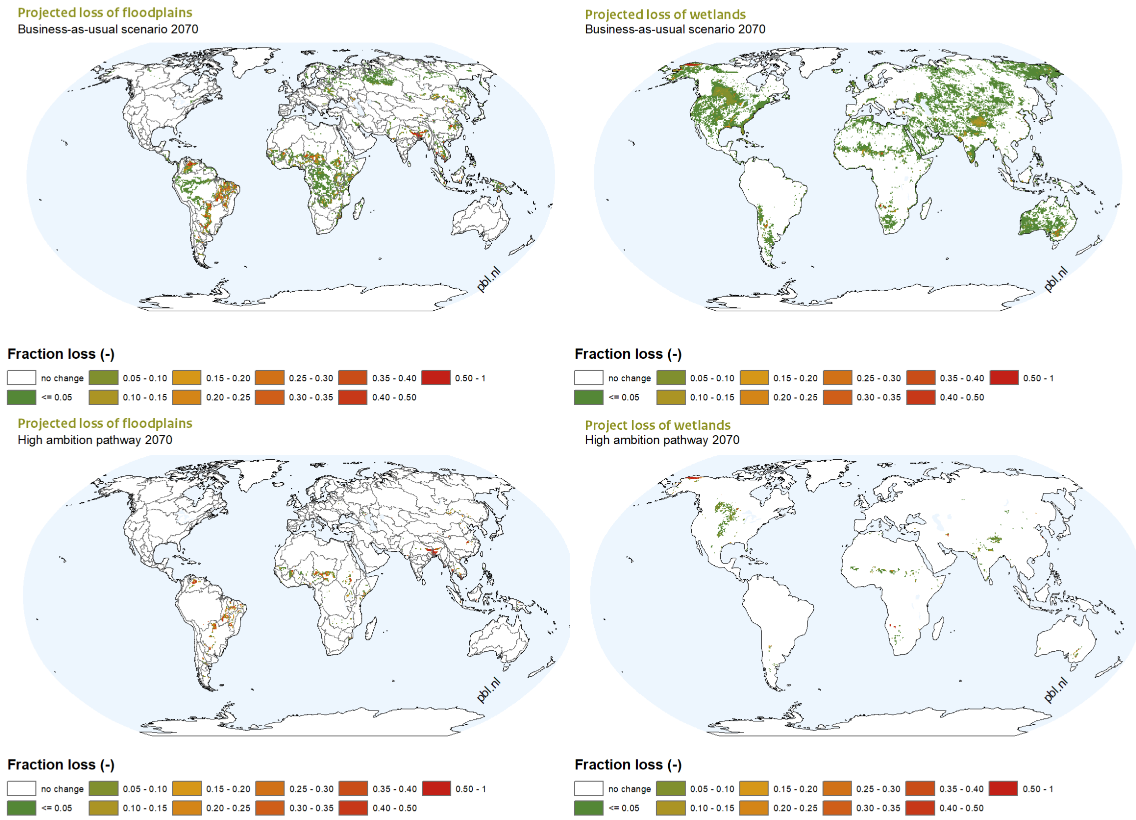
4.3 Wetland areas

In the 1990s, globally there was 3,674,000 km² of floodplain wetlands and 4,591,000 km² of other types of wetlands (GLWD: Lehner & Döll, 2004). The model results from IMAGE-GLOBIO indicate that, by 2015, significant parts of these wetlands were lost due to agricultural and urban expansion; 970,000 km² (26%) of floodplain wetlands, and 647,000 km² (14%) of other wetlands. This a considerable decrease, but it is, however, possible that a part of the wetland area reported in the GLWD was in fact already used for instance for livestock grazing, or seasonal or wet cropland. In these model calculations, the areas converted are assumed to be consistent with the conversion of other natural land cover types like forests and rangelands, according to their existence in the cells where the land use claims occur (as reflected in the terrestrial MSA).

In the Business-as-usual scenario (SSP2), the wetland loss would increase to 1,156,000 km^2 (31%) and 685,000 km^2 (15%) by 2070, respectively. In the SP-co land-use scenario, the loss of floodplain wetlands would be somewhat less (1,124,000 km^2) but for other wetlands even some more (710,000 km^2) than in SSP2. This is due to a somewhat higher demand for farmland in this scenario (less intensive agriculture).

However, the wetland protection and restoration policy as adopted in the High ambition pathway would restrict the loss to 564,000 km^2 and 166,000 km^2 respectively. These are the minimum areas that would be needed for the agricultural expansion and for which there is no alternative in the current grid cell. The difference between the projected and the minimum loss may therefore be regarded as the protection and restoration potential. This amounts to 592,000 km^2 floodplain wetlands (16% of the GLWD area) and 519,000 km^2 (11%) other wetlands; together this is 1,110,000 km^2 (13%) globally. These areas are more or less equally found over most river basins (Figure 4.3).

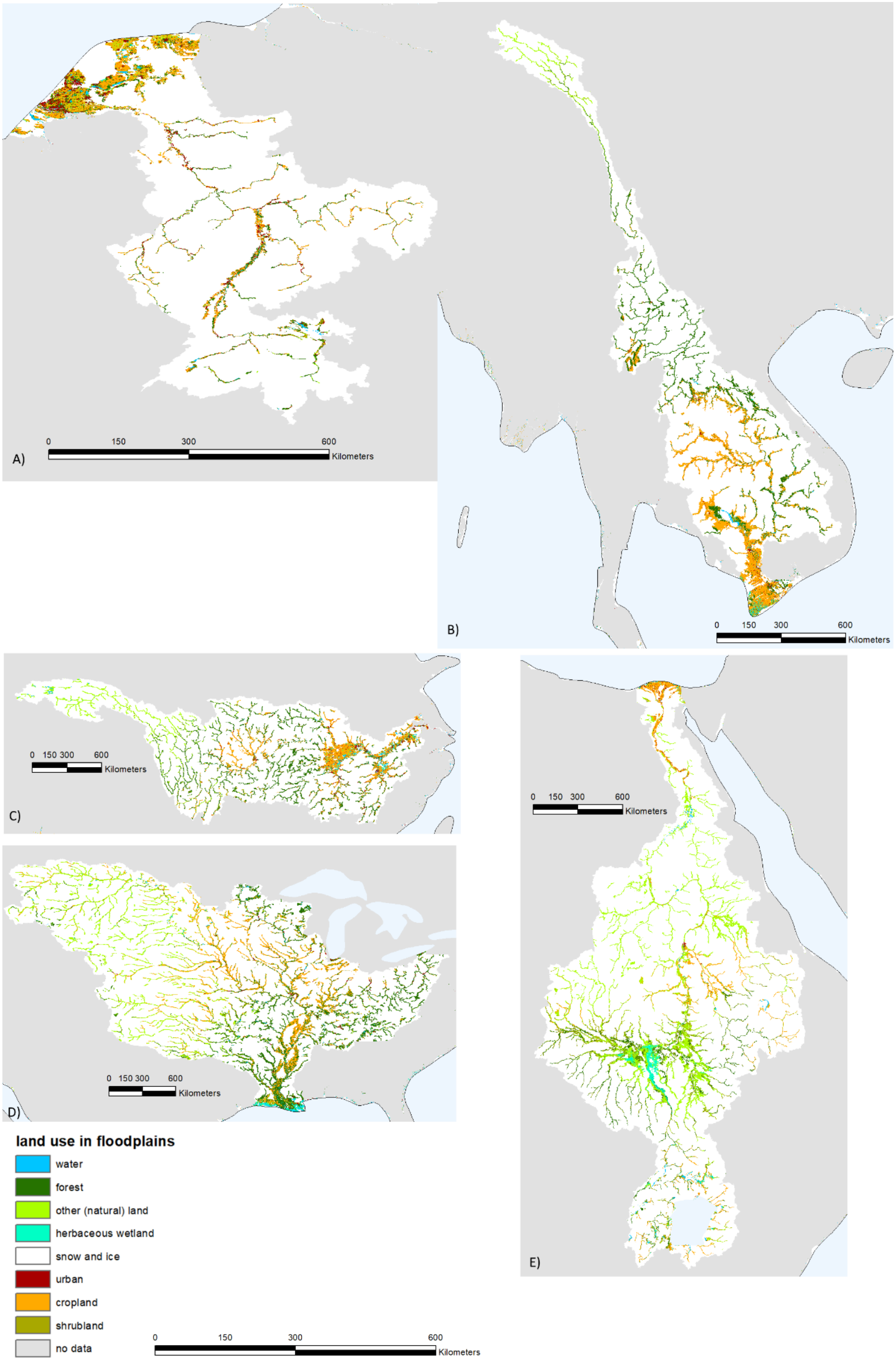
Figure 4.3
Projected loss of floodplain and non-floodplain wetlands, as fractions per grid cell, in 2070. Business-as-usual scenario and High ambition pathway.



Overall, in the Business-as-usual scenario, the global wetland area would decrease by 3% between 2015 and 2070. In the restoration scenario it would increase by 13%.

We also looked at the actual land-use in floodplains (i.e. the zones around rivers which are inundated at least 1:1000 years) as an alternative way of estimating the restoration potential, which we mentioned in section 2.2. This was analysed by means of the Copernicus PROBA-V dataset (Buchhorn et al. 2020), available for 1992 and 2015 on a 100 m resolution. According to these data, the total area of river floodplains amounts to $9.8*10^6$ km², 68% of which was still occupied by natural areas and about 30% ($3*10^6$ km²) by cropland (in 2015), however very unevenly distributed (see Figure 4.4 for some examples). This $3*10^6$ km² would represent the maximum restoration potential of floodplain wetlands (if it is possible to move the cropland to fields farther from the river). Note that these areas differ from the GLWD data; this is likely due to differences in definitions, assumptions, and data sources.

Figure 4.4.
Land-use in 1:1000 floodplains, 2015. A) Rhine; B) Mekong; C) Yangtze; D) Mississippi; E) Blue Nile.

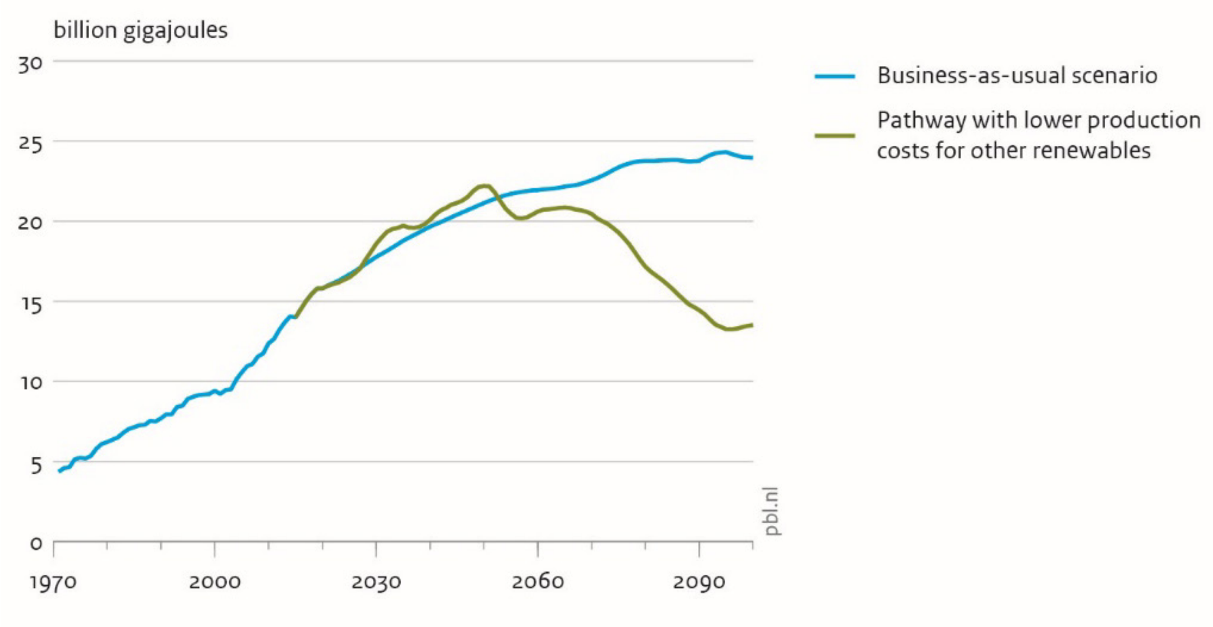


4.4 Dams and river flow

4.4.1 Number of dams

The future need for hydropower in the energy mix is dependent on electricity demand, climate policy targets, and production cost projections, as implied in the TIMER model. The projected hydropower capacity according to TIMER in the Business-as-usual scenario (RCP6.0) will gradually increase from the current $15*10^9$ to about $25*10^9$ GJ/y in 2100 (Figure 4.5). To compare: under RCP2.6 assumptions, the '2 degrees scenario', the production would first increase faster but drop below the Business-as-usual scenario after 2070.

Figure 4.5
Projected global hydropower production in billion gigajoules per year



For this estimated increase in hydropower production, the model projects the construction of 1250 new plants this century – on top of existing dams – of which 300 big dams with reservoirs. These will predominantly be located in Asia, Africa, and South America, as indicated on the map in Figure 4.6 below. The remaining plants would be constructed as 'diversion canal plants', which are assumed to have a more limited impact on river ecology than hydropower plants.

While the TIMER projection of capacity increase is consistent with other estimates by Zarfl (2015) and IEA (2021), the number of plants is about three times lower than reported by Zarfl (2015) in the FHRED database: 1250 plants instead of 3700, as included in Figure 4.6 below. Most of these plants are expected to be built in the coming 20 years, as illustrated in Figure 4.7 (regional graphs can be found in Gernaat et al. 2022). Of these plants, TIMER only projects 300 dams to have reservoirs, and the remainder to be diversion canal plants. This is the result of the algorithm for the cost/benefit optimisation of power production, which is applied at the IMAGE region level. As such, there is a preference for larger systems, of which, ultimately, a smaller amount would be needed. It is unclear whether this will actually be the case in practice, as decisions on hydropower construction will be based on additional criteria alongside cost/benefit optimisation. These decisions could also be made on other political or national levels, therefore differing per country.

Figure 4.6
Projected capacity of future dams in Megawatt

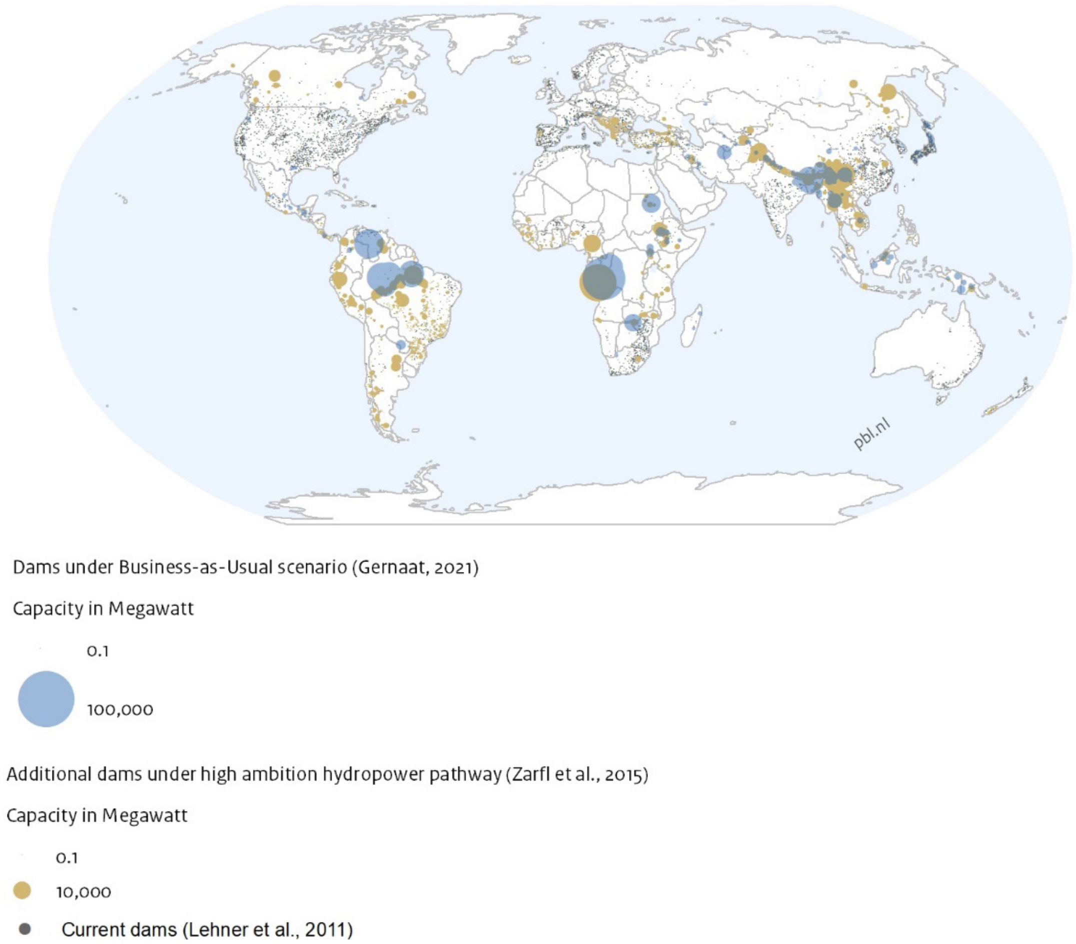
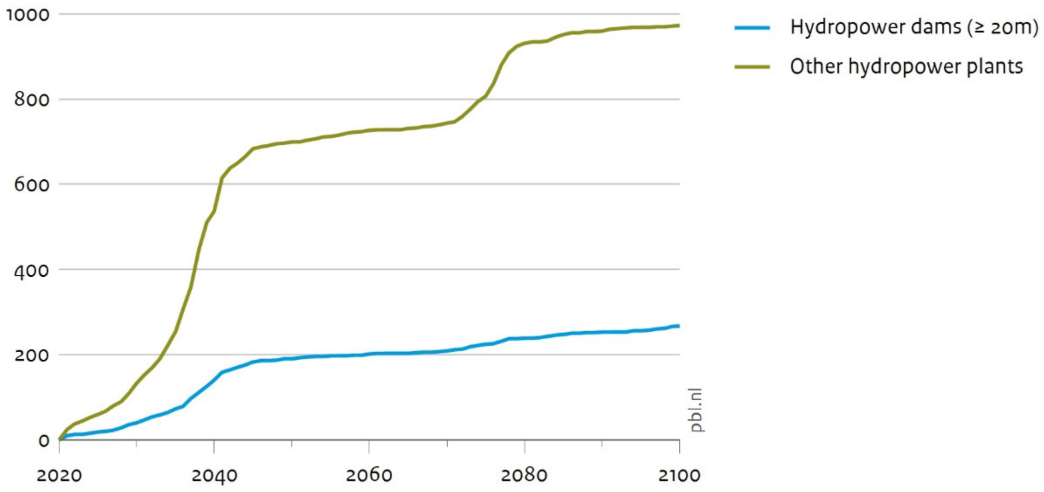
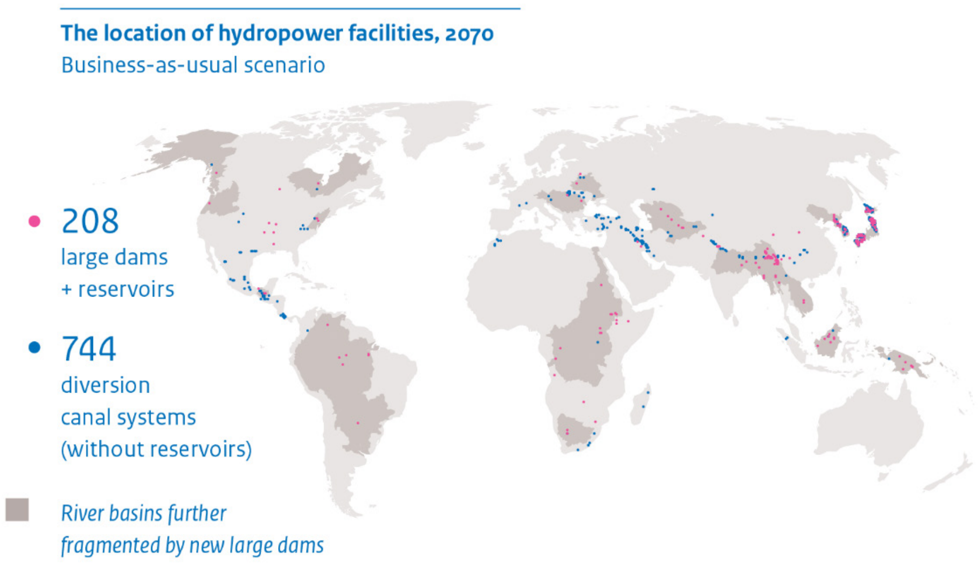


Figure 4.7
Cumulative number of new hydropower plants projected after 2020

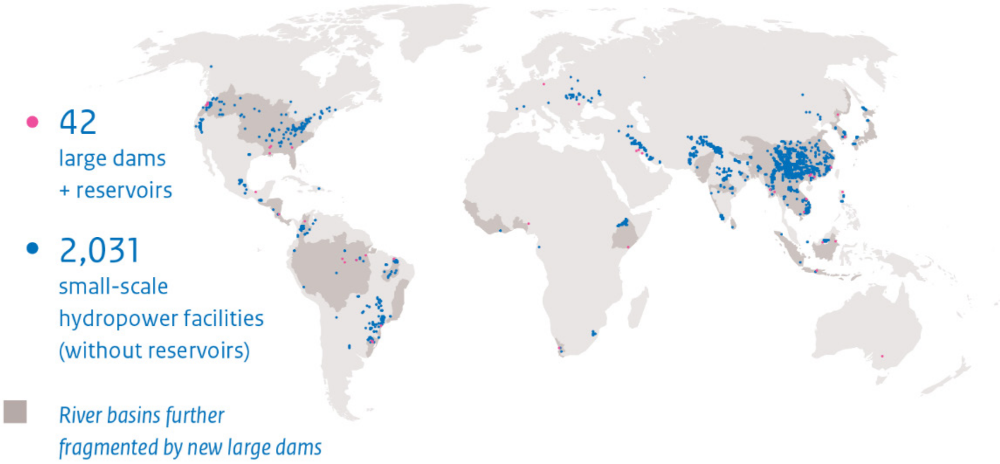


In the Moderate ambition pathway and High ambition pathway, which include restrictions on location, size, and type of dam, the model projects a shift from large dams to more and smaller installations, especially diversion canal systems (Figure 4.8).

Figure 4.8
The location of dams in a Business-as-usual scenario, moderate ambition pathway, and high ambition pathway



Moderate ambition pathway



High ambition pathway

Source: PBL; IMAGE/TIMER

The TIMER results indicate a high sensitivity to the assumptions made concerning the future electricity production costs of various energy sources. For example, in the 'renewable energy (*_re*)' scenario, it is assumed that the costs of solar power in particular would decrease faster than now assumed in the Business-as-usual scenario; in other words, it would experience a steeper so-called 'learning curve'. Indeed, in the 'renewable energy (*_re*)' scenario, solar power would gradually outcompete hydropower, leading to a decline in demand for the latter from about 2060 to the current level or even lower in 2100, as demonstrated in Figure 4.5. This scenario implies that the construction of a large number of hydropower plants would only be a temporary need; this would, however, require policy (and budget) to once more remove the then-obsolete dams. These costs are, however, not included in the TIMER model. The same level would be reached much sooner in case of restrictions placed on building dams, as used in our ecological scenarios. According to TIMER, the decrease in hydropower in the 'renewable energy (*_re*)' option can easily be met by an equal increase in other renewables. This does differ per IMAGE region, as some countries are more dependent on hydropower than others.

4.4.2 Effects on rivers

These dam scenarios discussed above will affect the flow status of rivers. Currently, only 37% of the rivers longer than 1000 km are still free-flowing over their entire range (Grill et al. 2018) and additional rivers are to be expected to lose this status in the future, as confirmed by the TIMER projections. In the Business-as-usual scenario, additional rivers will be affected in the Himalaya, the Caucasus, Eastern Europe, North America, South America, and Africa. This will be moderated or avoided in the ecological scenarios. The dam scenarios also affect the Flow Deviation, being the difference in seasonal flow pattern between disturbed and undisturbed situations, as used in GLOBIO-Aquatic to compute its effect on biodiversity intactness (see next section, 4.5), and the Environmental Flow Compliance as used in LPJmL. Moreover, the dam scenarios were used to estimate the effects on riverine fish, by the FishSuit model (see section 4.7).

4.5 Aquatic biodiversity intactness

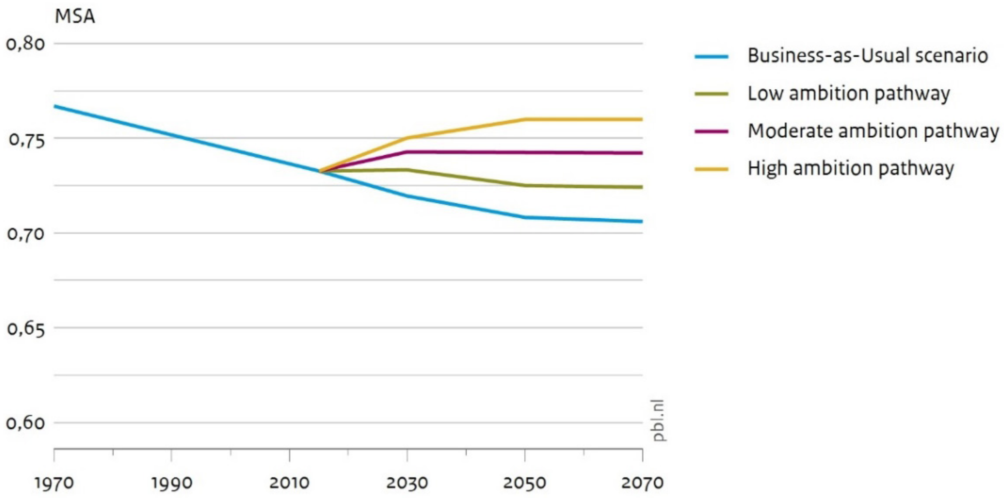
In Chapter 3, we discussed the specific methodology for projected trends in Biodiversity intactness, also known as Level of original freshwater biodiversity, or MSA-Aquatic. These trends were calculated for rivers, lakes, floodplain wetlands, and isolated wetlands, as well as the fraction 'good' (i.e. > 0.8). As stated earlier, MSA values range between 0 and 1. For wetlands, as for terrestrial ecosystems, biodiversity intactness has both a quantitative (area) and a qualitative (disturbing factors) aspect, as the wetland area may decline because of land-use or climate changes (see section 4.3). For rivers and lakes, only the quality aspects are relevant, as their surface areas are considered to remain constant.

In this section, we report the results for rivers and for lakes as well as the combined results for all water ecosystems, as global averages and geographical data on maps and difference maps.

4.5.1 Rivers

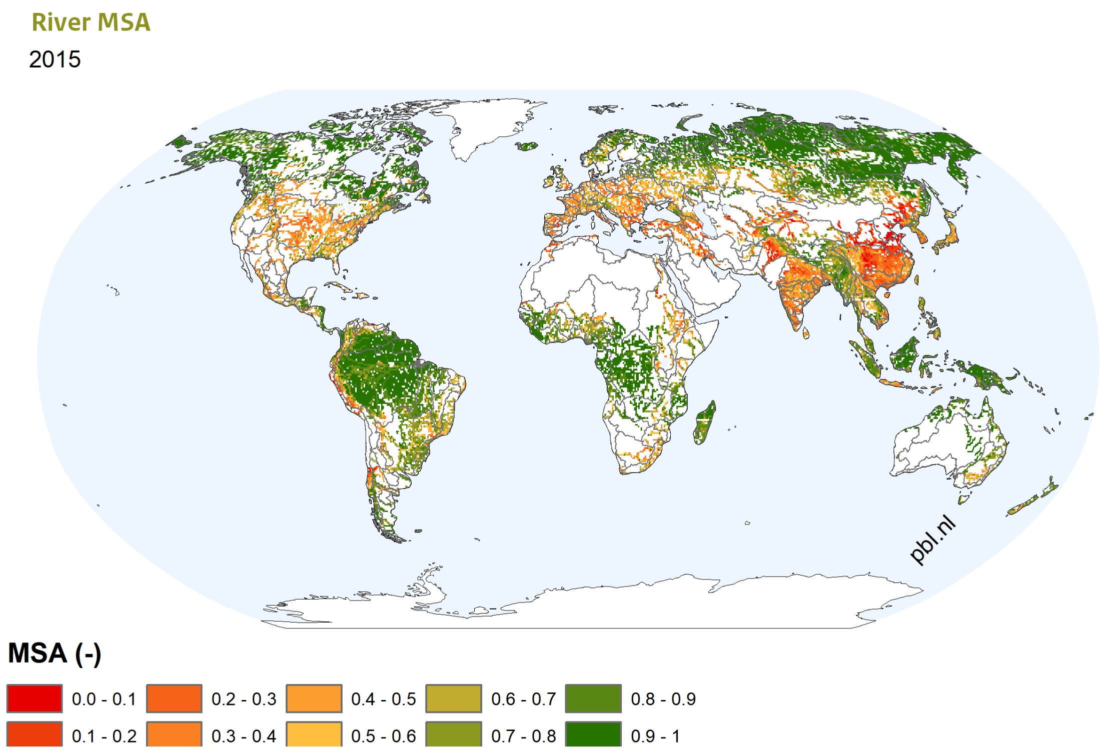
In the model, the MSA of rivers is affected by water quality and hydrological disturbance. The global average has declined from 0.77 to 0.73 between 1970 and 2015 and will further decline to 0.71 in the Business-as-usual scenario (see Figure 4.9). In the High ambition pathway, the MSA will - on average - recover to close to the 1970 value. It should be kept in mind that these numbers are global averages, in which regional differences are flattened out. This applies to all global curves. This flattening has even more effect for freshwater than for terrestrial results, as a relatively greater area freshwater occurs in the boreal zone which is less affected. The maps are more informative to see the large regional differences.

Figure 4.9
Projected global-averaged aquatic MSA of rivers



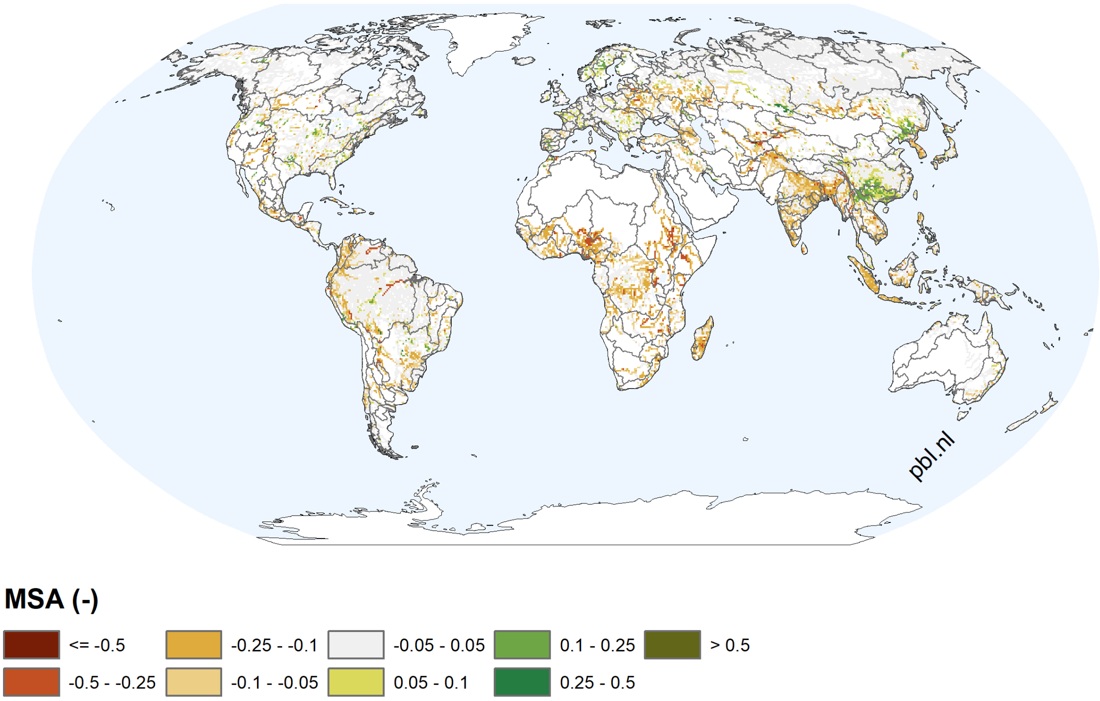
The maps (Figure 4.10) show that the results differ significantly among river basins. Between 1970 and now, many Asian rivers have further deteriorated, while European rivers have somewhat improved. For most rivers in Africa and South America, further deterioration is expected in the future in the Business-as-usual scenario, while this scenario projects some improvement, though no recovery, in Europe, North America, and, particularly, Asia.

Figure 4.10
MSA of Rivers 2015; Business as Usual 2070; High ambition pathway 2070.



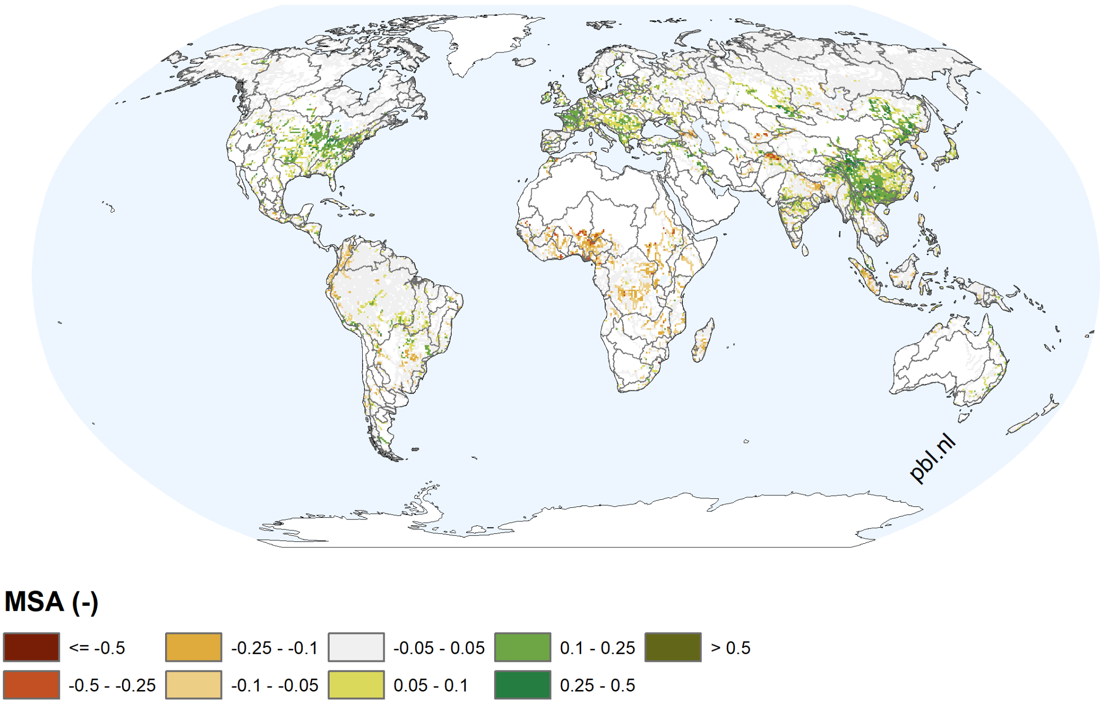
River MSA

Business-as-usual scenario 2070 vs. 2015



River MSA

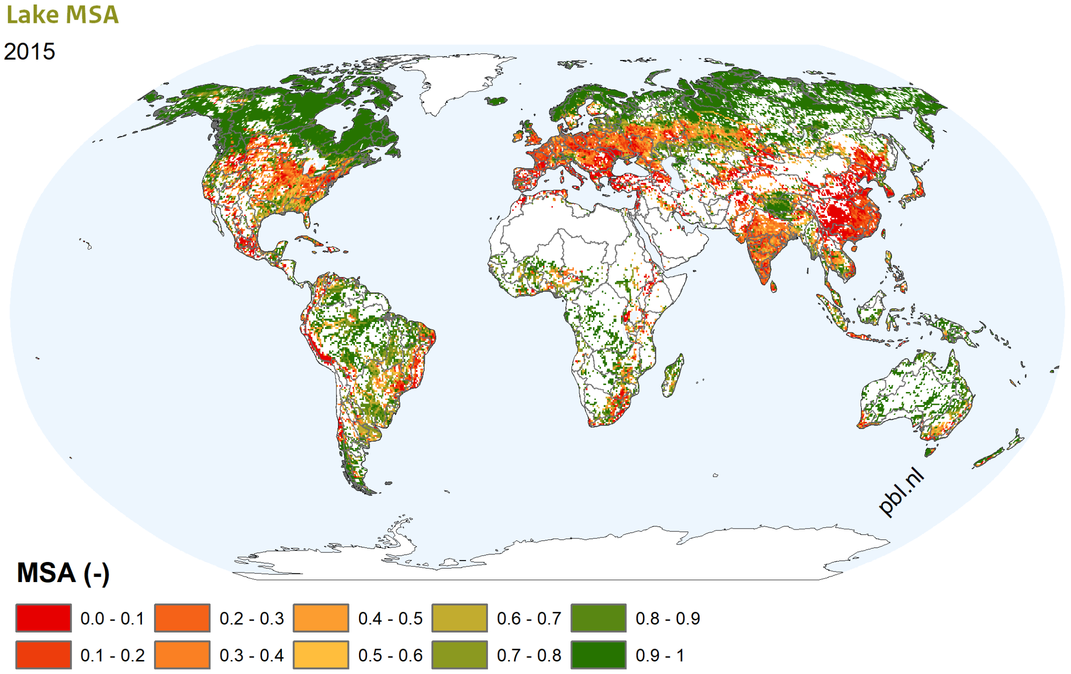
High amibition pathway 2070 vs. 2015



4.5.2 Lakes

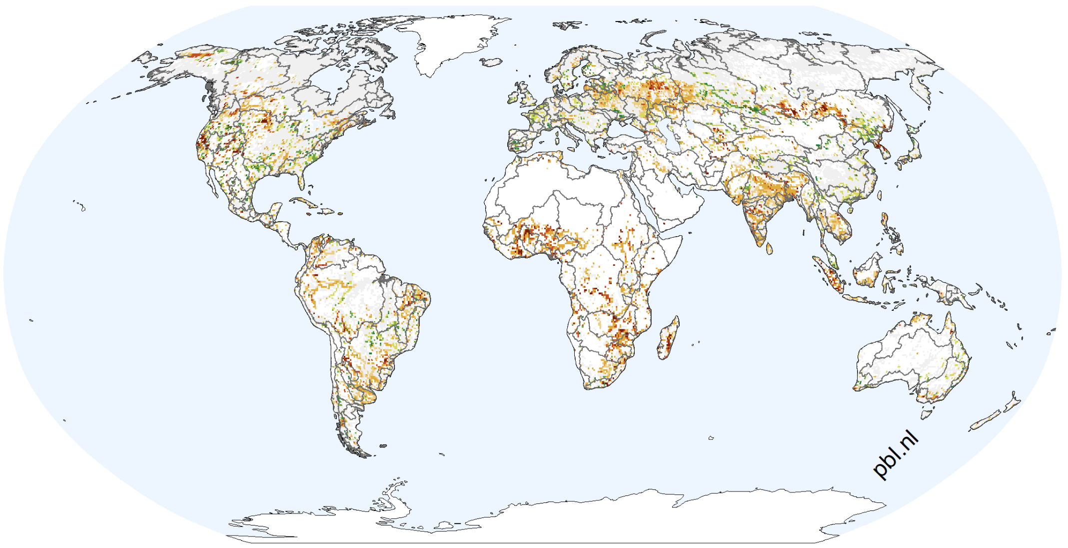
The modelled MSA of natural lakes, as affected by water quality in the current model, is projected to further decrease in the Business-as-usual scenario, with a restoration to 1970 values in the High ambition pathway, as shown in Figure 4.11. Geographically, the MSA is lowest in the regions and river basins with higher nutrient loading, which are mainly found in agricultural and highly populated regions. The Business-as-usual scenario shows a further decrease in most regions except for Europe and some parts of USA and China. In the High ambition pathway, some improvement is projected in many more regions, however, with India, Africa, and parts of South America as notable exceptions.

Figure 4.11
MSA of natural lakes 2015; Business-as-usual scenario 2070; High ambition pathway 2070.



Lake MSA

Business-as-Usual scenario 2070 vs. 2015

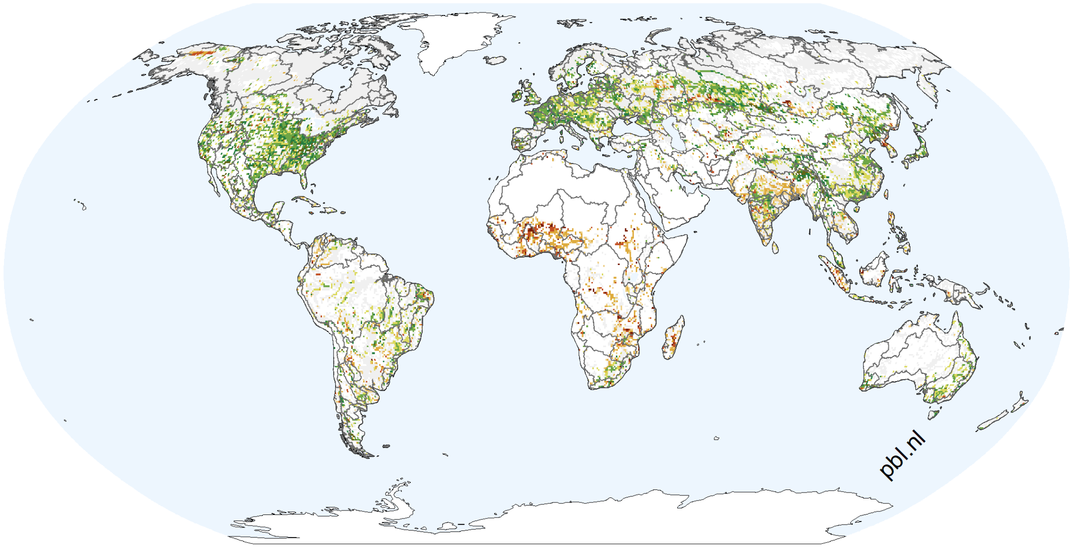


MSA (-)

<= -0.5
-0.5 - -0.25
-0.25 - -0.1
-0.1 - -0.05
-0.05 - 0.05
0.05 - 0.1
0.1 - 0.25
0.25 - 0.5
> 0.5

Lake MSA

High ambition pathway 2070 vs. 2015



MSA (-)

<= -0.5
-0.5 - -0.25
-0.25 - -0.1
-0.1 - -0.05
-0.05 - 0.05
0.05 - 0.1
0.1 - 0.25
0.25 - 0.5
> 0.5

4.5.3 Average aquatic MSA

In summary, we calculated the level of original freshwater biodiversity (%), area-weighted averaged for rivers, lakes, and (floodplain and non-floodplain) wetlands. Therefore, this indicator includes the combined effect of all modelled factors.

In the Business-as-usual scenario, the MSA will further decline in most tropical and temperature regions because of various increasing pressures, including nutrient emissions, dam construction, and wetland conversion. The High ambition pathway, on the other hand, will lead to a modest improvement in some regions but will, on average, not result in recovery either (see Figure 4.12). This is not entirely unexpected; pressures from dams and nutrient emissions do not differ much in this pathway compared to today. In the projection, the effects of increased population and economic development have, at the global scale, just been neutralised. The MSA might be even lower, as some pressures, such as toxic stress, overexploitation, and invasive species, were not (yet) included in the model.

From a geographical perspective, the biodiversity of freshwater ecosystems is already under high pressure in large parts of the world, especially in the densely populated and/or economically more developed parts of the temperate and tropical zones (Figure 4.13). This is in line with other studies, such as IPBES (2019) and Feio et al. (2022). Human pressures on river basins in boreal (subarctic) regions remain low between 2015-2070; indeed, relatively high biodiversity levels are still found there, as well as in the Amazon and Congo river systems. Some improvement is even projected in China, Europe, and North America, though no recovery, especially in Asia. In temperate and tropical zones, on the other hand, river basins will continue to face much higher pressures, as further deterioration is expected in most river basins in Africa and South America in the Business-as-usual scenario. This is due to decreasing water quality. In comparison, the High ambition pathway projects some improvement in many more regions, though not in India, Africa, and parts of South America. Though prevented in this pathway, dam construction (on top of the existing ~40,000 known large dams) is expected to increase in the river basins in South- and East Asia, the Caucasus, the Balkans, Africa, and South America. Finally, the protection or restoration of 13% of wetlands will contribute to the overall improvement in some regions, but will not compensate for the decline in regions with large population increases, such as in parts of Africa.

Figure 4.12
Projected global-averaged aquatic total MSA

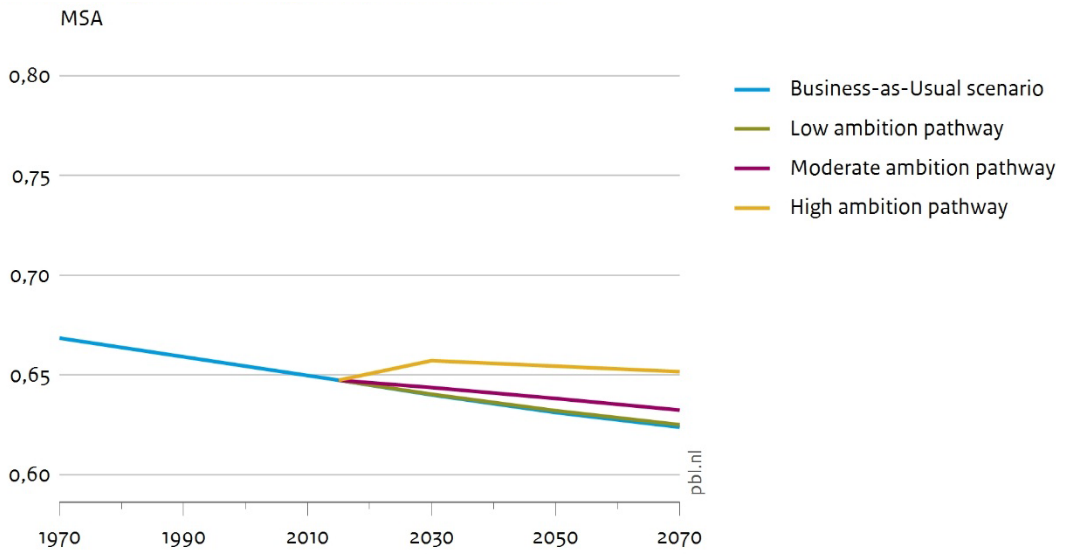
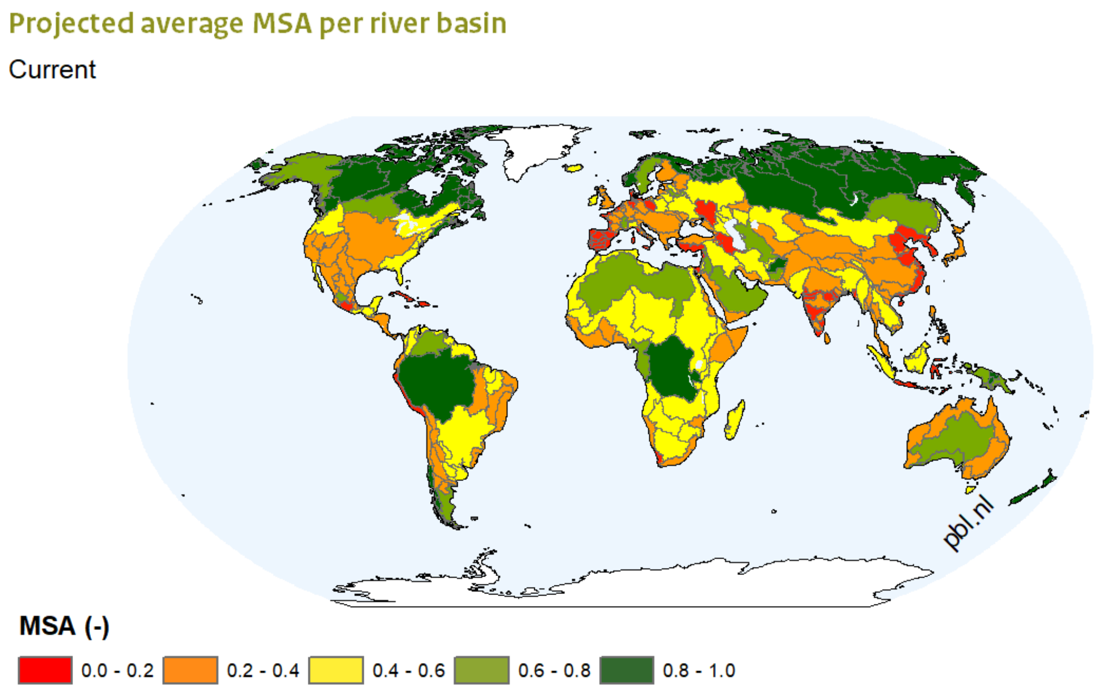
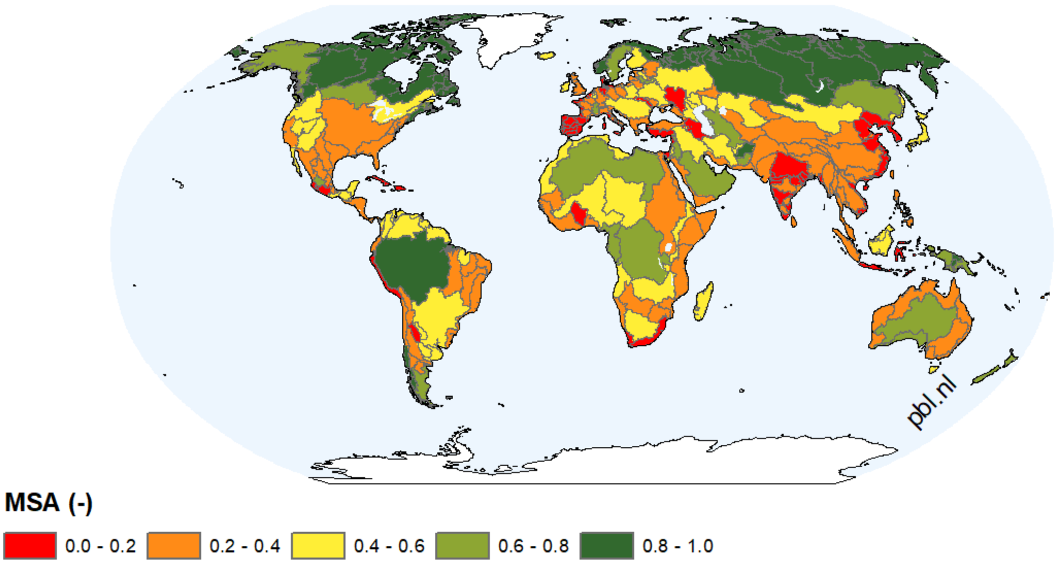


Figure 4.13.
Average aquatic MSA 2015; Business-as-usual scenario 2070; High ambition pathway 2070.



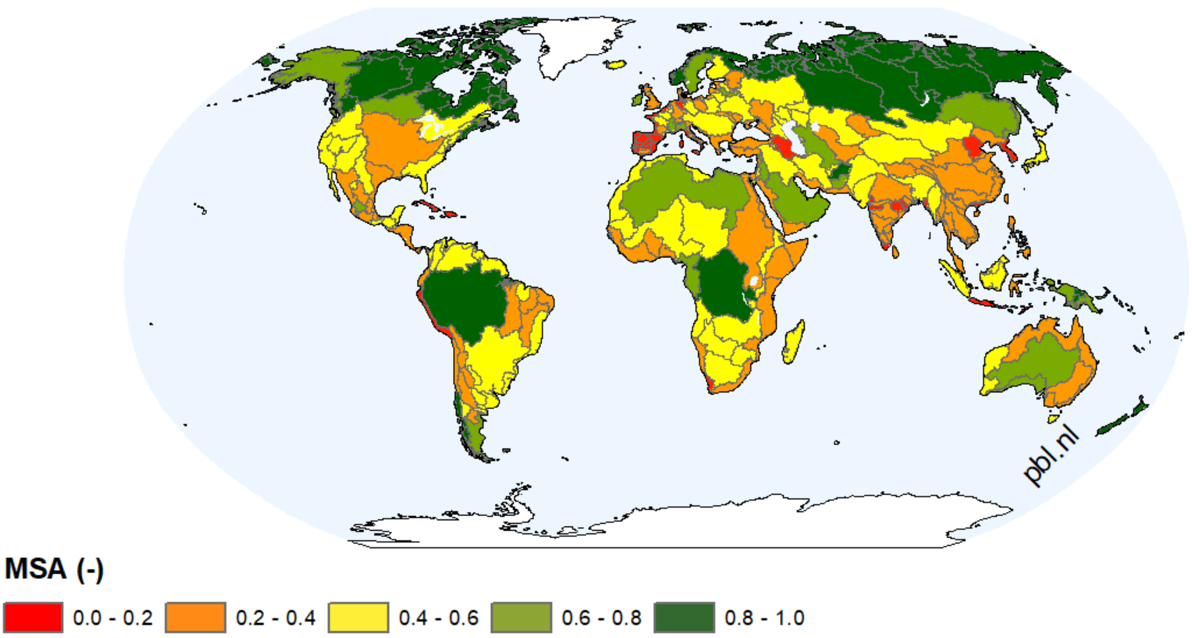
Projected average MSA per river basin

Business as usual scenario 2070



Projected average MSA per river basin

High ambition pathway 2070



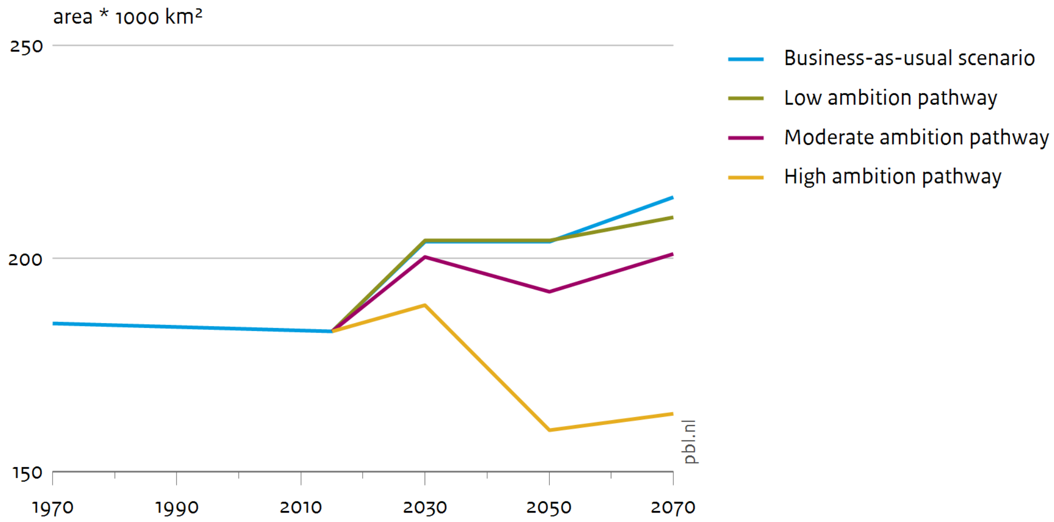
4.6 Harmful algal blooms in lakes

Harmful algal blooms (HABs) are labelled harmful for a reason; these algae colonies, mostly consisting of cyanobacteria in freshwater ecosystems, threaten ecological quality and biodiversity, while simultaneously causing health risks for both humans and animals due to their production of various toxins. Global warming is raising the water temperatures which, in combination with high nutrient emission levels, further increases the risk of HABs in lakes (Paerl and Huisman 2008, 2009).

For natural lakes as well as reservoirs, these algal blooms are modelled as dependent on nutrient loading (TN and TP) and water temperature. We compared the modelled algal concentrations with the World Health Organisation (WHO) guidelines for health risks in surface waters that are used for recreation or as a source of drinking water (Chorus and Welker 2021, being an update of Chorus and Bertram 1999; see also Carvalho et al. 2013). The 2021 WHO guidelines define, in terms of biovolume values, a 'Vigilance level' at values between 1 and 4 $mm^3\ L^{-1}$, and 'Alert level 1' when values are between 4 and 8 $mm^3\ L^{-1}$; using cyanobacterial chlorophyll concentration these values are 3 and 12 mg m^{-3} and 12 and 24 mg m^{-3}, respectively. An assessment of toxins concentrations determines whether the highest 'Alert Level 2' is reached when urgent actions are needed.

According to the model, in 2015 approximately 20% of the world's lakes and reservoirs showed concentrations of potentially harmful cyanobacteria exceeding the WHO 'vigilance level' for health risk, of which half also exceed the 'alert level 1' (Figure 4.14). This percentage is projected to increase with approximately 10% in the Business-as-usual scenario, but will show a 10% decline in the High ambition pathway.

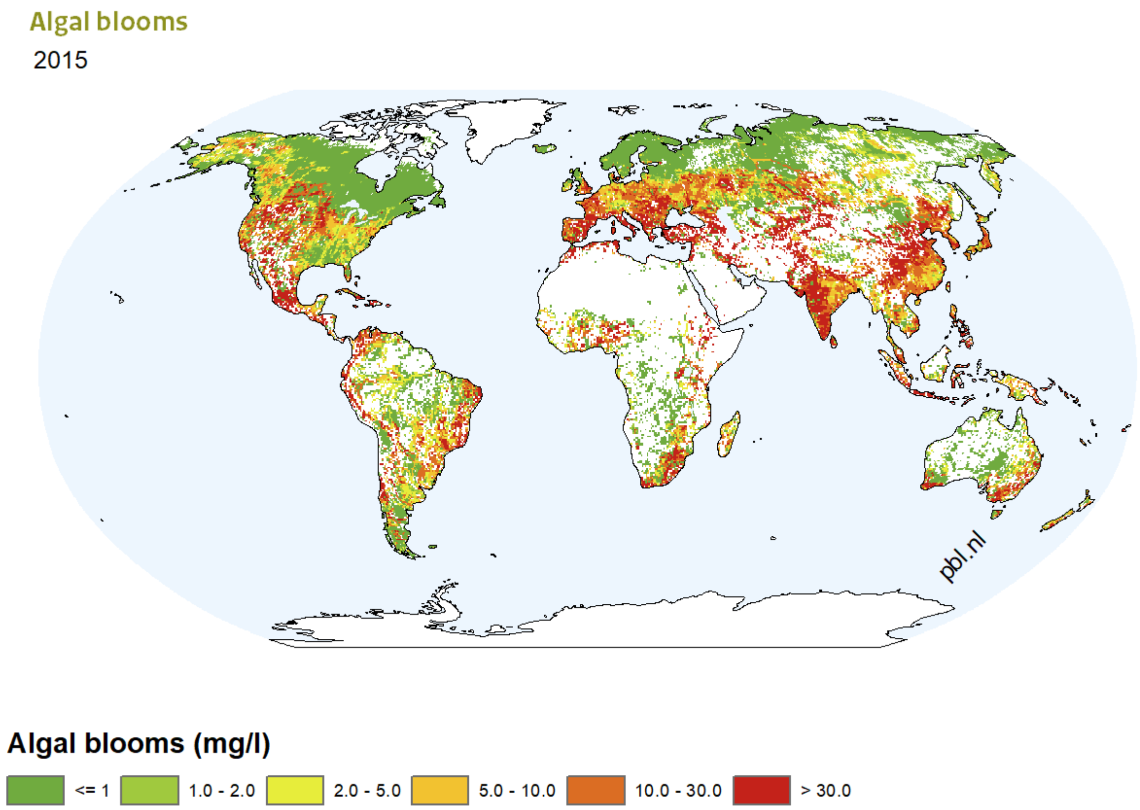
Figure 4.14
Global area of freshwater systems with moderate to high risk of harmful algal blooms



The regions with the highest algal bloom risk coincide, in fact, with the highest MSA loss in lakes in China, India, West Asia, Europe, the USA, and some lakes in Africa and South America (see Figures 4.15 and 4.16). Lakes in the boreal river basins are least affected. (Note that the MSA has been calculated for natural lakes only, whereas the algal blooms applies to both natural and artificial lakes). In the Business-as-usual scenario (Figure 4.15b), a further deterioration is projected for Africa and South America, while improvement is expected in parts of heavily impacted regions such as China, Europe, and the USA. There is also a relative increase in some northern regions, which may be attributed to climate change, particularly to the rise in water temperature.

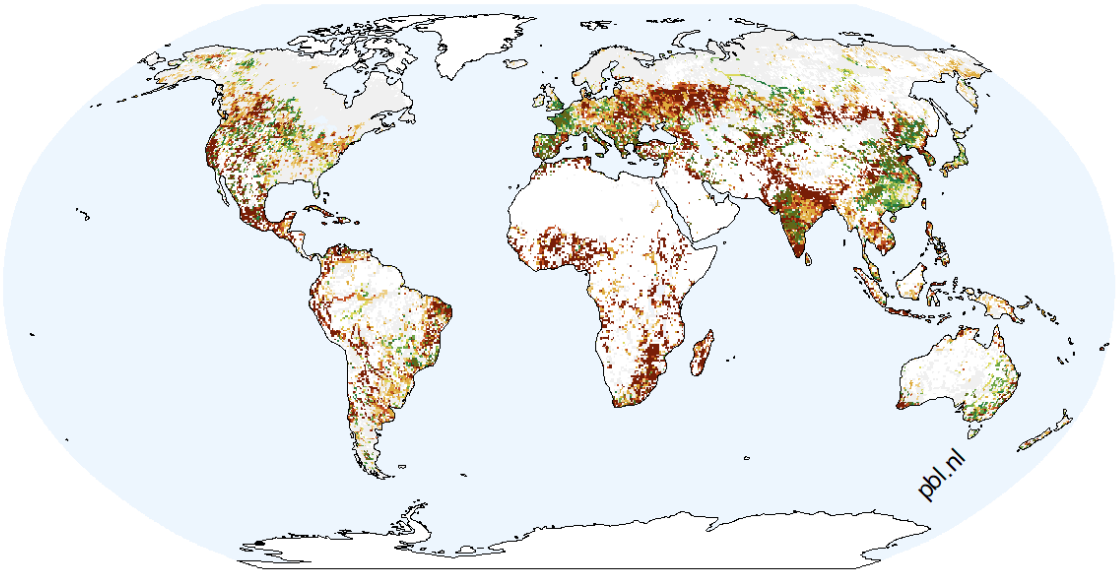
The most ambitious pathway, shown in Figure 4.15c, is projected to encourage recovery in many regions, except for Africa and South America. A decrease in lakes with associated health risks is particularly expected in China, Europe, and North America; this decrease is attributable to nutrient reduction. Global warming will, however, increase the overall risk of algal blooms. To counteract this effect and mitigate the high risk of HABs, more ambitious efforts on nutrient emission reductions are encouraged.

Figure 4.15
Algal blooms in 2015; Change in algal blooms Business-as-usual scenario 2070; change in algal blooms high ambition pathway 2070.



Algal blooms

Business-as-usual scenario 2070 vs. 2015

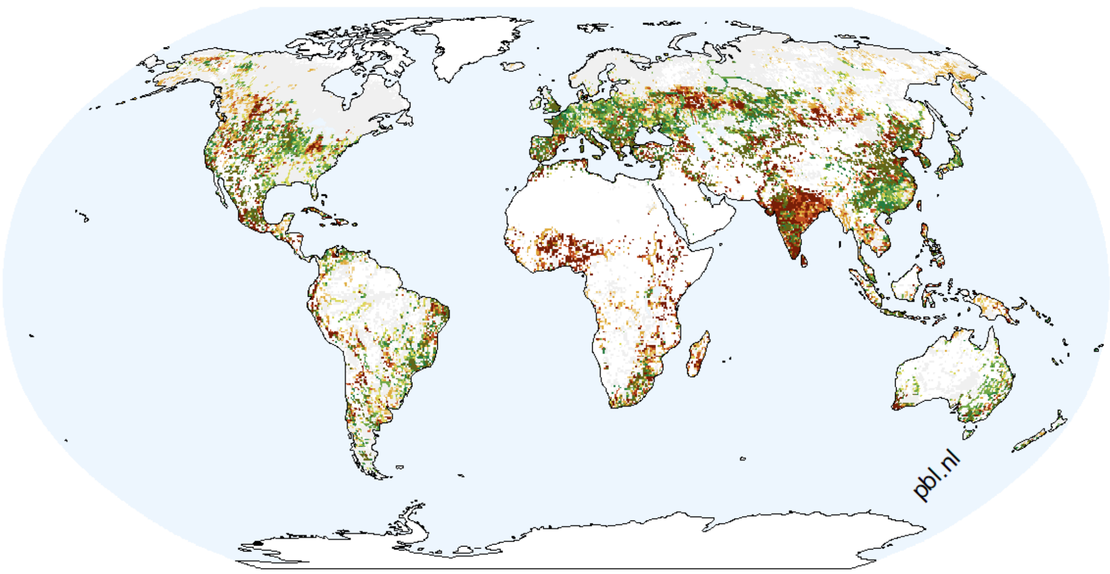


Change in algal blooms (mg/l)

<= -10.0	-5.0 - -2.0	-1.0 - 1.0	2.0 - 5.0	> 10.0
-10.0 - -5.0	-2.0 - -1.0	1.0 - 2.0	5.0 - 10.0	

Algal blooms

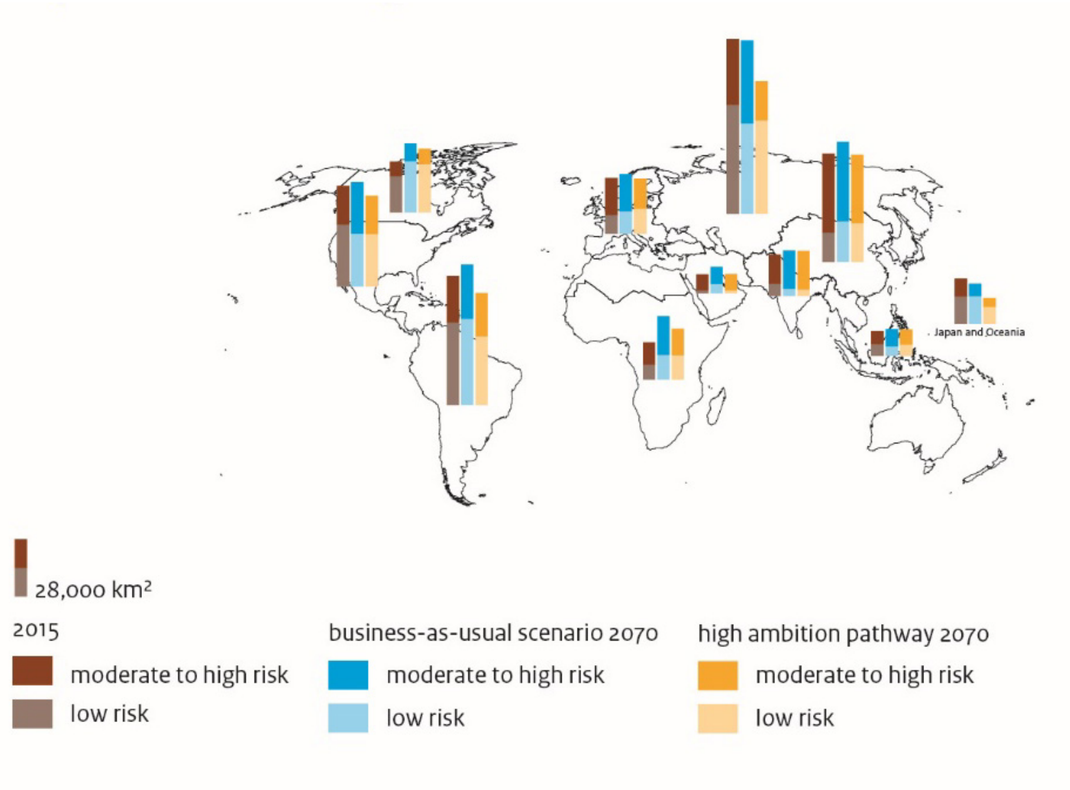
High ambition pathway 2070 vs. 2015



Change in algal blooms (mg/l)

<= -10.0	-5.0 - -2.0	-1.0 - 1.0	2.0 - 5.0	> 10.0
-10.0 - -5.0	-2.0 - -1.0	1.0 - 2.0	5.0 - 10.0	

Figure 4.16
Projected lake areas with algal bloom risk



4.7 Fish habitat suitability

Chapter 3 described how the FishSuit model (Barbarossa et al. 2020, 2021) simulated the effects of (a) climate change and (b) fragmentation by dams on the habitat suitability of riverine fish species. This section describes the model results.

4.7.1 Climate change

Projections show that, with a temperature increase below 3.2° (above pre-industrial values) and no dispersal potential for fish to escape to cooler places, 36% of the riverine fish species would have at least 50% of their current geographical range exposed to higher temperatures. Tropical, semi-arid, and Mediterranean regions are particular hotspots of climate threat, and especially vulnerable regions include South America, southern USA, southern Europe, the Middle East, South and Southeast Asia, and parts of sub-Saharan Africa (Barbarossa et al. 2021).

If maximum dispersal within river catchments and ecoregions was possible, the fraction of fish species with >50% of their range threatened is projected to be limited to an average of 8%, with the same regional differentiation. Conserving and restoring fish dispersal opportunities may help reduce the potential impact of temperature increases. This indicates that strategies to reduce the number of dams in river systems, can effectively contribute to mitigating climate change effects on fish populations.

4.7.2 Fragmentation by dams

As described in section 4.4, however, the reality is that dispersal is restricted in many rivers because of dams. FishSuit simulated the effects of current and future dams on the fragmentation of geographical occurrence ranges of riverine fish species, where more fragmentation corresponds to a lower 'connectivity index' (CI). The global average CI is 73 (± 28)% for non-diadromous and 86 (±19)% for diadromous species (Barbarossa et al. 2020). The Connectivity Index is especially low in river basins in North America, Europe, the Middle East, South Africa and South-, East- and Southeast Asia. These largely coincide with the non-free flowing' rivers as shown by Grill et al. (2019). Due to future dam construction in the Business-as-usual scenario, the CI will further decrease by more than 5% globally (Figure 4.17), especially in basins in North America, South America, Africa, and South- and Southeast Asia (Figure 4.18). This may (but not necessarily) imply a population decrease or extinction of species and will diminish the species' resilience to climate change. In the High ambition pathway, the CI decrease is avoided as we assume in this scenario that all new hydropower plants will be small and that they will have only a small effect on fish migration.

Figure 4.17
Average decrease in Connectivity Index 2015 – 2050;

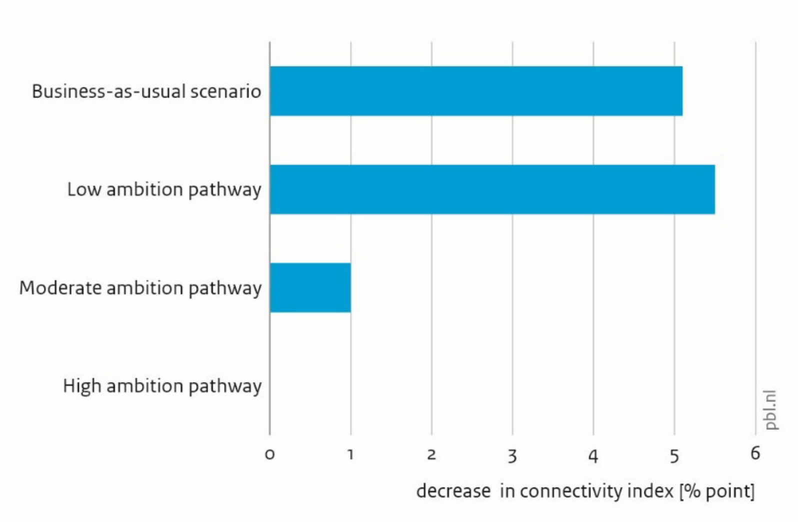
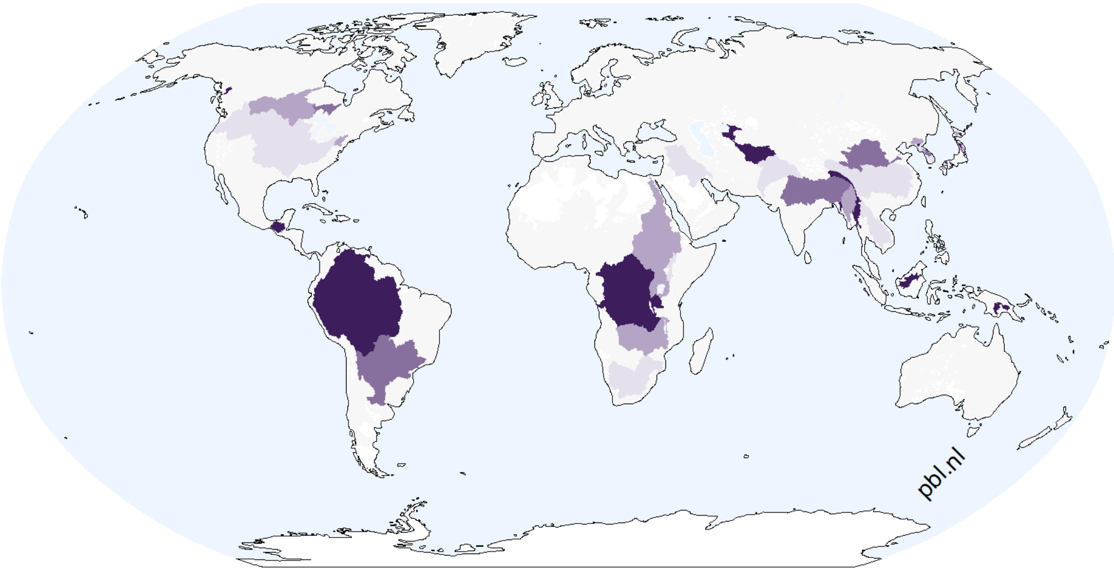


Figure 4.18
Decrease in Connectivity Index per river basin 2015 - 2050, business-as-usual scenario



4.8 Conclusions and discussion

4.8.1 Conclusions

Globally averaged, in an SSP2/RCP6.0 future, the ecological quality and biodiversity of freshwater ecosystems is set to further deteriorate. There is slim chance of recovery, as even the High ambition pathway, where the overall projected pressures from dams and nutrient emissions do not differ much from today, does not project this. Indeed, in this pathway the increases in pressures due to population increase and economic growth will only just be neutralised.

There are, however, significant geographical differences. In the boreal zone the overall quality will remain good in all pathways, as the included pressures remain low. In currently highly affected regions such as Europe, North America, and China, the High ambition pathway will lead to improvements, but not in Southern Asia, while an even further deterioration is projected in Africa and South America.

The measures in land-use, agriculture, and wetland restoration will contribute considerably to ecological improvement. There are still large possibilities for wetland restoration. The urban wastewater scenarios, however, will not lead to improvement in aquatic ecosystems as treatment does not develop at the same pace as sanitation.

In the High ambition pathway, connectivity and environmental flow, and the biota dependent on these factors, can, at most, be kept at the current values. Restoration will require the removal or redesign of existing barriers. Economic incentives implied sooner on other renewables may considerably limit the need for hydropower extension and related dam construction.

A structural ecological improvement will require a further reduction of the pressures on ecosystems. To achieve this, more fundamental societal changes will be needed. Elements of this transition will be (but not analysed in this study, as explained in the Introduction): circular economy, a strong reduction of agricultural land use in combination with food waste reduction and a reduced consumption of animal products, strong reduction in water use, rethinking the need and construction of dams for renewable energy production, and a large-scale wetland restoration effort, far beyond the level in our High ambition pathway. Some of these elements were included in the 'SP_is' scenario described by Immovilli and Kok (2021) and Kok et al. (2023), which combined extensive nature protection with 'integrated sustainability' measures.

4.8.2 Discussion

Our modelling results are broadly in line with existing studies that describe the quality of aquatic ecosystems and biodiversity at a global scale, despite significant differences in scope, methods, indicators, and taxonomic selection. Most studies confirm, as do our results, a continuous decline in the quality and biodiversity of these ecosystems, and name as most influential factors land use, eutrophication, and flow disturbance. These studies also confirm that the most relative decline has occurred in the most populated and economically highly developed regions (Feio et al. 2023 for rivers, Filazzola et al. 2020 for lakes, Davidson and Finlayson 2018 for wetlands, and Rajib et al. 2023 for wetlands, to name a few). Our study produces a reasonable representation of general trends, but, like any study, there are limitations and uncertainties which hamper more differentiated projections. These limitations mostly lie in scale and schematisation problems, the choice of included factors, limitations of input models, lack of data, and limitations of the biodiversity models.

There are, however, large differences between indicators when comparing global studies. One example is the Living Planet Index (LPI; Almond et al. 2020), which shows a much steeper decline for freshwater species than does our global-averaged MSA indicator. Potential reasons include differences in taxonomic groups (LPI focuses on vertebrates), geography (LPI is based on species trends, and tropical ecosystems are generally more species-rich than cold-temperate or polar water systems), and included stressors (MSA does not cover all pressure factors at time of writing). Hence, it is likely that the global-averaged MSA even underestimates the decline of freshwater biodiversity. Another example is that there is a reported 76% decline in the populations of migratory riverine fish species over the past century (Deinet et al. 2020). Our model shows a smaller decline but in the same regions, though it also applies different methods and indicators.

Several uncertainties adhere to the modelling approach used in this study:

- We chose the grid cell-based schematisation for its relatively easy linkage with GIS-based land-use models. Indeed, it is a good fit for global (area-based) hydrological models, but less so when attempting to describe water bodies as lakes, rivers, and floodplain wetlands. The water and nutrient flow to and through rivers and lakes is only roughly described and cannot be correctly attributed to pressures such as urban emissions or river dams. Moreover, local features of water types are not accounted for. Adoption of a network-based schematisation of the water system, smartly combined with the (existing) land-use grid, may be a promising tool. Existing tools such as the HydroSheds database (already used in the FishSuit model for the river dam locations) can provide a basis for this.

- The current model chain omits factors such as the (over)exploitation of biotic and abiotic aquatic resources and the effect of invasive species, both of which are mentioned as key issues by Tickner et al. (2020). It also omits emissions of toxic substances (including 'new' substances such as microplastics and pharmaceuticals). Moreover, climate change effects are only partially included (i.e. temperature effects on fish and algal blooms are included, but not yet the effects of drought). Updates are in development but not yet operational, and therefore the model projections are likely to be over-optimistic.

- For the factors that we *did* include, there are restrictions set by the available model chain. A 'mixed agricultural landscape' as proposed in the 'Sharing the Planet' scenario could only be implemented in IMAGE-GLOBIO as a proxy (Kok et al. 2023). Likewise, the buffer zones could only be implemented as a 'bulk' area per grid cell. In the nutrient modelling chain, lakes with a long residence time had to be left out because GNM projected an unrealistically high retention in those cases.

- The energy model TIMER could only handle scenarios for future dams, not for current ones (e.g. adaptations or removal (e.g. Foley et al. 2017)). Moreover, the hydropower potential did not account for expected future declines in river discharge.

- The wetland projections were hampered by the lack of historical wetland maps (from before c. 1995); therefore, the restoration potential of wetlands that disappeared before 1995 could not be assessed.

- A general restriction of GLOBIO-Aquatic (and its input models) is that interactions between pressures are neglected. Likewise, the model chain mostly lacks feedbacks between ecological quality and pressures/drivers, so that (co)benefits of ecological quality improvements for food production, water resources, health, economic development, or other 'ecosystem services' are not used in those other models. This is still a field in development.

Following on from these issues, we list several recommendations for future studies:
- Improve the GLOBIO-Aquatic model by updating or expanding existing modules for nutrients, dams, and climate factors, and adding factors that are currently lacking, such as overexploitation, invasive species, and chemical stress;
- Integrate different pressures in a more sophisticated way than just multiplication;
- Improve the joint interpretation of MSA and other ecological indicators;
- Replace the current 30'-grid-based schematisation of the surface water system by a network-based schematisation. This would allow for a more realistic allocation of water bodies and their place in the network, improved allocation of run-off and nutrient loadings (e.g. retention times of lakes, attribution of urban and diffuse loadings), dam locations, variable area of lakes (important in view of climate change), and the possibility to distinguish water types (e.g. small/large rivers, or lakes on different soil types);
- Improve the integration of wetlands with other land cover categories in the maps, both for actual, future, and historical situations;
- Extend the energy model TIMER with a decision support system at the catchment scale which includes ecological criteria for dam allocation and removal (see e.g. NCEA 2021);
- By these and other means, improve the link between the different abiotic and biotic models in the model chain, to allow inclusion of a wider range of ecological scenarios.

5 Biodiversity pathways in the context of the SDGs and ecosystem services

In this chapter, we make some remarks concerning the links between the ambition pathways and the Sustainable Development Goals (SDGs; United Nations, 2015). At a glance, all modelled ecologically based options also have beneficial effects on other water-related challenges. All measures that improve water quality for ecosystems, such as more sustainable agricultural practices, buffer zones, and urban wastewater treatment, are equally beneficial for all human functions that rely on clean water, including drinking water, aquatic food (fish catch and fish farming), and water for agriculture and industry. A reduction of harmful algal blooms also benefits human health. Wetland restoration contributes to water storage and flood protection and thereby also to climate adaptation, as well as water purification and climate mitigation (carbon storage). Moreover, increased water use efficiency is positive for food production, whereas restrictions on hydropower dams have co-benefits for sediment flow and coastal protection, as well as for water quality, fish catch, and the survival of human communities. Some trade-offs, on the other hand, include land use area in relation to wetlands (depending on e.g. management), risk of CH_4 emissions, and the additional challenges for the transition to sustainable energy sources that hydropower dams generate (which does depend on the assumptions for production costs of the other renewables in question). We list such co-benefits and trade-offs on the nature-based topics analysed in this study in Table 5.1 below, and Figure 5.1 shows (non-exhaustive) links between these nature options, ecosystem services, and the SDGs.

From this 'quick scan' analysis, it is clear that protection, restoration, and good management of aquatic ecosystems, alongside being positive for biodiversity itself (SDG 14 and 15), potentially has many co-benefits for the SDGs on water (6), food (2), health (3), climate (13) and sustainable communities (11), extending to secondary benefits for several others like poverty reduction (1), sustainable economy (12), conflict reduction (16), partnerships (17) and innovation (12). Potential trade-offs are competition for space and reduced hydropower production (SDG 7). Costs can be either higher or lower (and different for different stakeholders).

In many ways, spatial aspects are crucial, i.e. the effects depend not only on the extent but also on the location in the rivers or catchment areas where the protection or management measures are taken. At places where competing interests cannot be combined, compromises and/or a combination of ecological and technical options will be necessary.

To improve the evaluation of these ecosystem services, we recommend a closer integration between the biotic and abiotic models, and including feedbacks between ecosystem services and drivers to show the effects of the actual use of these services. It would also be beneficial to extend the analysis with socio-ecological models to account for governance aspects, stakeholders' interests and evaluation of trade-offs. These are challenges for future modelling work (Chaplin-Kramer et al., 2024).

Combining all the projected impacts of the modelled measures in terms of the SDGs (Figure 5.2), results in a moderate improvement of most of the SDGs in the High ambition pathway, compared to a moderate decrease of most SDGs in the Business-as-usual scenario. Trade-offs will be in energy production and in the economic growth of some traditional sectors. Trade-offs in land use area will probably be outweighed by the positive aspects of sustainable agriculture such as the higher reliability and more efficient use of resources.

Table 5.1
Co-benefits and trade-offs of the nature-based topics analysed in this study for other SDGs.

Topic	Biodiversity benefits (SDG 15)	Co-benefits (SDG #)	Trade-offs (SDG #)
Sustainable agriculture, mixed landscapes	Water quality (Habitat protection)	Water quality (6) Health (3) Sustainable food production (2,1,12) Aquatic food (2,1) Marine life (14)	Land area (2, 9)
Riparian buffer zones	Water quality Habitat protection	Water quality (6) Climate resilience (13)	Land area (2)
Wetland restoration	Habitat protection Water quality Connectivity	Flood protection (1, 13) Climate resilience (13) Water availability (2) Water quality (6)	Land area (2, 9) CH_4 emission (13)
Increased water use efficiency	Flow	Food production (2, 12) Conflicts reduction (16, 17)	
Dam restrictions	Flow Connectivity (Water quality)	Erosion control (6, 11, 14) Aquatic food (2) Sust. cities and communities (11) Conflicts reduction (16, 17)	Hydropower production (7)
Urban wastewater treatment	Water quality	Water quality (6) Health (3) Food (2) Marine life (14)	

Overall, we conclude that an ecosystem-based approach is an essential pathway for an integrated solution to many environmental problems and contribute to a sustainable human society, acknowledging that healthy ecosystems lie at the basis of human society. This is in line with the ‘wedding cake’ representation (instead of the ‘block’ or ‘wheel’ representation) of the SDGs put forward by SRC (2016) and Obrecht et al. (2021), placing the ‘biosphere goals’ (SDGs 6, 13, 14 and 15) at the bottom, the societal (1-5, 7, 11, 16) in the middle, and the economic goals (8-10, 12) at the top. A related conclusion from the FWC project as a whole (Ligtvoet et al., 2023a) is that the restoration of ecological quality goes hand-in-hand with the solution of most other water-related challenges (Figure 5.3); that is, with hydropower as the main exception.

Prerequisites for these integrated solutions are improving the policy coherence between sectors and across decision levels, and strengthening the global water governance. These topics are not part of this study but are further addressed in Ligtvoet et al. (2023a,b).

The sustainable management of water systems based on a system approach is one of the global transformation challenges. Other challenges we have to face include the transitions towards renewable energy production, sustainable agriculture, and sustainable cities, as well as building a circular economy. Strengthening social and ecological values, as well as mainstreaming water- and climate-related challenges in all development strategies, decisions, and projects, will be needed to really bend the trend of declining ecosystems and associated ecosystem services, and to enter a path towards a sustainable world (Ligtvoet et al., 2023a).

Figure 5.1
Main links (non-exhaustive) between the nature options analysed in this study, ecosystem services and the SDGs.

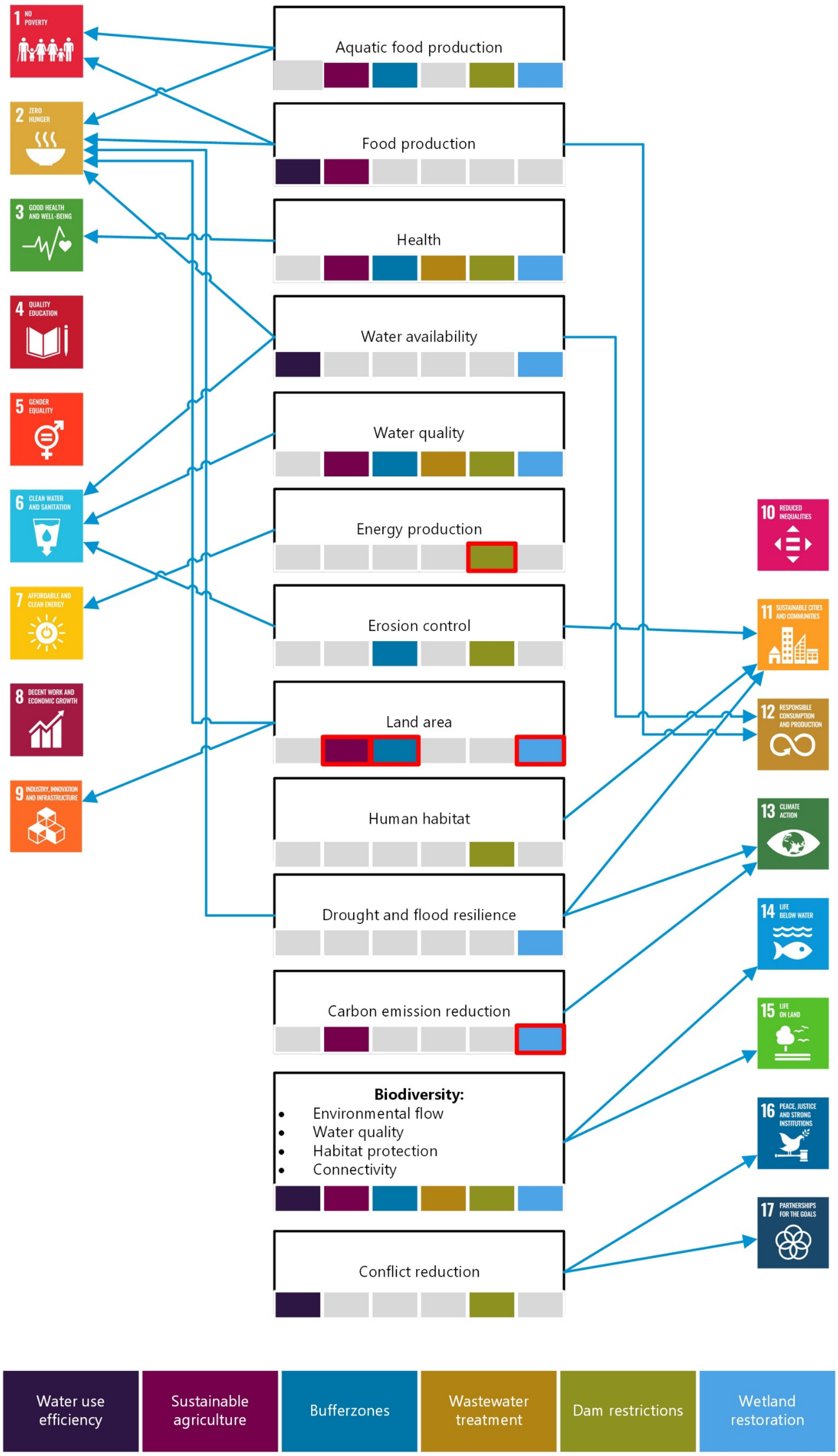


Figure 5.2

Estimated trend in SDGs up to 2070 for the Business-as-usual scenario and the high ambition pathway

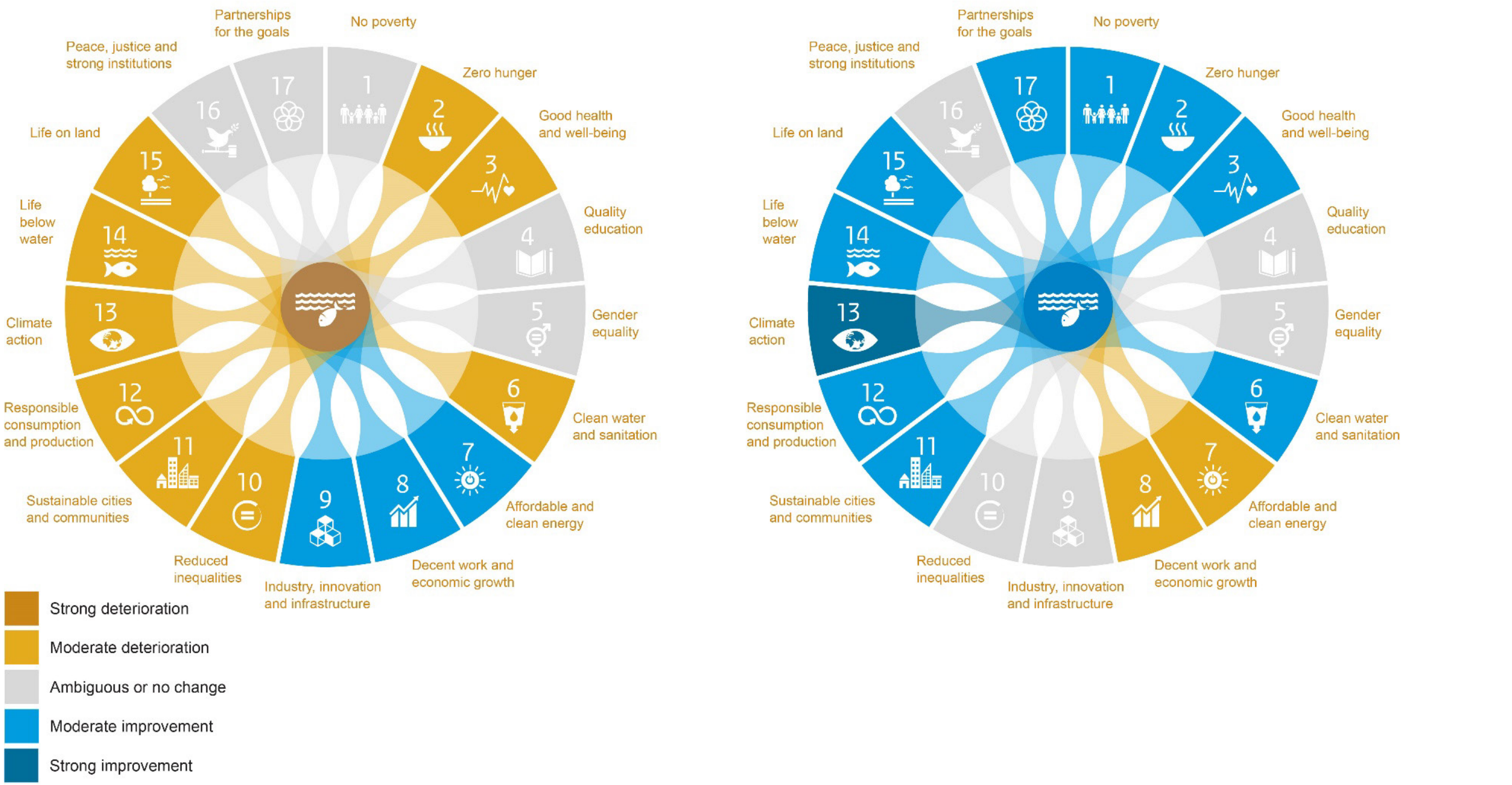
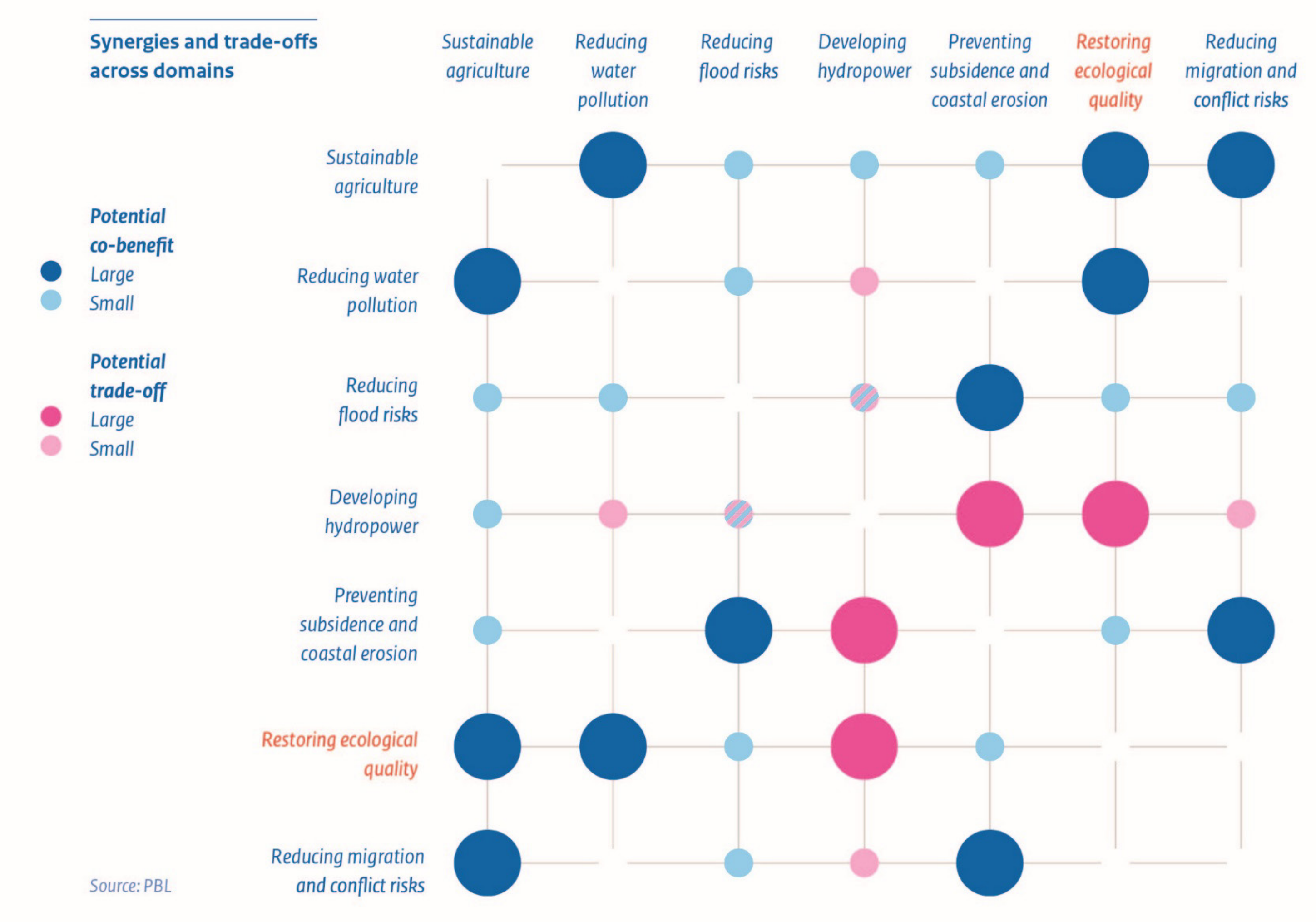


Figure 5.3
Synergies and trade-offs between water-rated challenges



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Appendix A: List of nature-based solutions

The following tables provide an overview of all nature-based approaches focussed on aquatic ecosystem, mainly based on the 2018 World Water Development Report (WWDR) (UN-Water 2018). The approaches are grouped in: preservation and restoration of ecosystems; reduction of (effects of) pressures; additional (created) nature-based solution (NBS). The following items are scored for each of these measures:

- its category, the second column: spatial (S), technical (T), management (M), social (S);
- the benefits for aquatic nature itself and for water-related ecosystem services (SDGs), columns three through seven;
- possible co-benefits with other SDGs, column eight;
- possible trade-offs, column nine.

Table 1
Effects on nature and nature's benefits to people: overview of aquatic nature-based solutions; preservation and restoration of ecosystems.

Options	Cat.*	Nature (SDGs 14, 15, 6)	Water supply (SDG 6)	Flood control (SDGs 11, 13)	Erosion control (SDG 12)	Water quality and health (SDGs 6,12)	Other (co)benefits (SDGs)	Trade-offs (on SDGs)
Forests	S, M	+	+	+	++	++	Wood	Land competition
Soils	M,T, S		+	++	++	+	Food (SDG 2)	
Riparian zones	S,M	+		+	++	++		Land competition
Isolated wetlands	S,M	+	+	+	+	+	Climate (SDG 13)	Land competition
Rivers, lakes and floodplain wetlands	S,M	+	+	+	+	++	Fish prod. (SDG 2)	Land competition
Mangroves, salt marshes	S	+		+	+		Fish prod. (SDG 2)	Land competition

Table 2
Effects on nature and nature's benefits to people: overview of aquatic nature-based solutions; reduction of (effects of) pressures.

Options	Cat.*	Nature (SDGs 14, 15, 6)	Water supply (SDG 6)	Flood control (SDGs 11, 13)	Erosion control (SDG 12)	Water quality and health (SDGs 6,12)	Other (co)benefits (SDGs)	Trade-offs (on SDGs)
Increase C-sequestration in water systems	M	+				+	Climate (SDG 13)	
Hydropower using bypass; reduce dams	T, S	Reduce --				+	Fish prod. (SDG 2). Sediment flow	Energy yield (SDG 7)
Decrease water demand	T,M, D	+	+					
Increase irrigation efficiency	T,M	+	+					
Good farming practices -> reduce nutrient pollution	T,M,S	+			+	+	Food production (SDG2)	
Reduce other pollution	T,M					+	Health (SDG 3.1)	
Water treatment	T	+			+	+	Health (SDG3.1)	
Reduce overfishing	M	+					Sustainable fisheries	
Sustainable aquaculture	M,S	+					Fish production	
Prevent invasive species	M	+						

Table 3
Effects on nature and nature's benefits to people: overview of aquatic nature-based solutions, additional (created) nature-based solutions (NBSs).

Options	Cat.*	Nature (SDGs 14, 15, 6)	Water supply (SDG 6)	Flood control (SDGs 11, 13)	Erosion control (SDG 12)	Water quality and health (SDGs 6,12)	Other (co)benefits (SDGs)	Trade-offs (on SDGs)
Water areas & greens in cities	T, S	+	+	+			Health; Climate adapt.	
Permeable pavements	T		+	+				
Green roofs etc.	T			+				
Treatment wetlands	T,M					+		