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Water, climate and aquatic-biodiversity risks

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Main messages

- Under the socio-economic SSP2 trend scenario, aquatic biodiversity intactness will further decrease, up to 2050, especially in Sub-Saharan Africa and parts of South America and Asia. These regions include river basins with a currently high aquatic species richness. In western Europe and North America, small improvements are foreseen.
- The main causes of aquatic biodiversity decline constitute increases in agricultural area at the expense of wetlands, eutrophication (from both diffuse and point sources), water abstractions, and dam construction for hydropower and irrigation. Climate change aggravates some of these problems.
- The combination of the SSP2 scenario and the RCP 8.5 climate scenario projects an increase in harmful algal blooms in lakes, due to an increase in nutrient emissions and water temperature.
- Prevention of aquatic biodiversity loss and restoration of already affected water systems require an integrated approach encompassing an improvement in water quality and restoration of river flow dynamics and wetlands. Opportunities for ecology-based solutions, such as in the framework of Integrated River Basin Management, are often missed.
- The increase in water temperature depends primarily on climate policies.

1.1.1 Introduction

This document describes the risks that current and future drivers and pressures pose to the functioning of freshwater aquatic ecosystems, the biota that depend on them, and the ecosystem services they provide. These drivers and pressures are climate change and socio-economic developments.

Trends so far

Currently, freshwater ecosystems—rivers, lakes and wetlands—are already seriously under threat and their use is being stretched to maximum capacity (MA, 2005; Revenga, 2005; Vorosmarty et al., 2010; Boelée et al., 2017). For example, since 1900, nearly 70% of the world's wetlands have been lost (Davidson, 2014), 70% of the world's rivers have become highly or moderately fragmented (Nilsson et al., 2005), many of the world's lakes, especially in the temperate and tropical regions, are heavily impacted by eutrophication (Paerl et al., 2011), and the loss of aquatic species is continuing at an even faster rate than that of terrestrial species (MA, 2005; Tisseuil et al., 2013). Wetland losses are continuing at a steady pace (CBD, 2014; Gardner et al., 2015), and the remaining wetlands are threatened or affected by hydrological changes, eutrophication, pollution and climate change.

Today's mere 1 °C of average global warming already is having an impact on most ecological processes in terrestrial, freshwater and marine ecosystems. These impacts span the biological hierarchy, from single genes to entire communities (Bellard et al., 2012, in: Scheffers et al., 2016).

These drivers and pressures lead to losses not only of natural habitat and biodiversity, but also of important ecosystem services, both regulating services (hydrological regulation, climate adaptation, water purification) and provisioning services (e.g. water supply, food provision), as well as cultural services, such as those for recreation (MA, 2005; Russi et al., 2013; WWAP, 2015). Wetlands deliver important contributions to key SDGs, such as on food supply, clean fresh water supply, and preserving life (Gardner et al., 2015; see Table 1 for an overview of wetland ecosystem services).

Table 1. Wetland Ecosystem Services and related ecosystem structures and functions (Russi et al., 2013)

Ecosystem services	Ecosystem structure and function	Examples of Valuation Studies
Coastal protection	Attenuates and/or dissipates waves, buffers winds	Badola and Hussein (2005), Barbier (2007), Costanza et al. (2008), Das and Vincent (2009), Bayas et al. (2011)
Erosion control	Provides sediment stabilisation and soil retention	Sathirathai and Barbier (2001)
Flood protection	Water flow regulation and control	Brouwer and van Elk (2004)
Water supply	Groundwater recharge/discharge	Acharya and Barbier (2000, 2002), Smith and Crowder (2011)
Water purification	Provides nutrient and pollution uptake, as well as retention, particle deposition	Byström (2000), Yang et al. (2008), Jenkins et al. (2010)
Carbon sequestration	Generates biogeochemical activity sedimentation, biological productivity	Jenkins et al. (2010), Sikamäki et al. (2012)
Maintenance of temperature, precipitation	Climate regulation and stabilisation	
Raw materials and food	Generates biological productivity and diversity	Sathirathai and Barbier (2001), Islam and Braden (2006)
Maintains fishing, hunting and foraging activities	Provides suitable reproductive habitat and nursery grounds, sheltered living space	Johnston et al. (2002), Barbier (2007), Smith (2007), Aburto-Oropeza et al. (2008), Sanchirico and Mumby (2009)
Tourism, recreation, education and research	Provides unique and aesthetic landscape, suitable habitat for diverse fauna and flora	Hammitt et al. (2001), Johnston et al. (2002), Carlsson et al. (2003), Othman et al. (2004), Brouwer and Bateman (2005), Birol et al. (2006), Birol and Cox (2007), Do and Bennet (2008), Jenkins et al. (2010).
Culture, spiritual and religious benefits, bequest values	Provides unique and aesthetic landscape of cultural, historic or spiritual meaning	Kwak et al. (2007)

The most important pressures on aquatic ecosystems worldwide are (MA, 2005; Revenga, 2005; Janse et al., 2015):

- disappearance of wetlands due to direct land-use changes;
- eutrophication and other pollution due to land-use changes in catchments as well as increasing urban emissions;
- hydrological disturbance of riverine systems due to dam construction and river regulations;
- increased water abstraction;
- climate change;
- overexploitation;
- invasion of exotic species.

Policymakers on global, national and regional levels are concerned about these deteriorations. Important, on a global level, are the Ramsar Convention (established in 1971) and the Convention on Biological Diversity (CBD) (since 1992). Despite the impressive Ramsar list of wetlands of international importance—in 2017 covering >15% of the world's wetland area (see www.ramsar.org)—the convention has not been able to stop the decline. Besides protection, it continues to stress the wise use of wetlands as one of the key elements. The Global Biodiversity Outlook 4 (CBD, 2014) concludes that inland water ecosystems are not well protected by the current protected area networks.

There is widespread consensus about healthy aquatic ecosystems being essential for the realisation of several of the recently adopted Sustainable Development Goals (SDGs), in particular goals 6.6 (protect and restore water-related ecosystems), 6.3 (improve water quality), 6.4 (reducing water scarcity) and 15.1 (ensure the conservation, restoration and sustainable use of inland freshwater ecosystems and their services, such as wetlands and drylands). The wise use of aquatic systems would also contribute to other SDGs, such as 2.1 (end hunger), 3.9 (reduce health risks from water pollution) and 13.1 (increase resilience to climate-related hazards). At the same time, there are potential trade-offs between certain SDGs that have to be addressed, such as 6.2 versus 6.3 (improved sanitation may deteriorate downstream water quality) and 7.2 versus 6.6 (hydropower compromises aquatic life).

Currently, there are several other global initiatives that aim to mainstream the protection and sensible use of aquatic ecosystems into broader society, by showing how intact aquatic ecosystems may contribute to other societal goals, how nature-based solutions (e.g. ecological water management) may help to solve water-related challenges, and how economic sectors may contribute to this (Kok and Alkemade, 2014; Boelée et al., 2017).

1.1.2 Goal

This document primarily presents our projection of the global state of aquatic biodiversity and ecosystem services for 2050 (compared against 2010 levels, i.e. the 'current' situation), as a function of future land-use changes, hydrological disturbance, climate change and other pressures. It identifies the hotspots of greatest past and future losses, discusses the main underlying causes, and relates our findings to those of other studies. On this basis, it discusses options for damage reduction or restoration, and the opportunities for ecology-based solutions.

Identification of the hotspots of greatest past and future losses is based on these two indicators:

- Mean Species Abundance (MSA), a biodiversity intactness index. This indicator is a measure of loss of aquatic biodiversity. It has been derived from a compilation of scientific studies where this indicator is quantified by comparing species composition in impacted lakes, rivers and wetlands to that in comparable, yet undisturbed, systems. MSA values for rivers, lakes and wetlands have been combined by area-weighted averaging into values for 'aquatic MSA'.
- The amount of harmful algal blooms (cyanobacteria) in lakes. These algae are potentially toxic and may lead to increased health risks, particularly in water bodies used for bathing and washing and for public water supply. Both eutrophication and climate change will generally increase phytoplankton blooms (Wilhelm and Adrian, 2008; EEA, JRC and WHO, 2008) and increase the dominance of harmful cyanobacteria in phytoplankton communities (Moss et al., 2011; EEA, 2017). More frequent extreme precipitation and run-off events are also expected to increase nutrient loading to waters and, thus, result in eutrophication. Climate change may increase harmful algal blooms in lakes as a direct result of temperature increase as well as climate-induced increases in nutrient concentrations (Schindler, 2001; Jeppesen et al., 2014; EEA, 2017)).

1.1.3 Methods and Analysis

Model set-up

The calculations were performed using the *GLOBIO-Aquatic* model, v. 1.3 (Janse et al., 2015), to assess the dominant human impacts on inland aquatic biodiversity and to be used in future projections. The model system consists of an empirical biodiversity model, coupled with a global water map and embedded in the IMAGE model framework (Stehfest et al., 2014), providing links to models about demography, economy, land-use change, climate change, nutrient emissions, and hydrology. We applied a catchment approach by including the spatial relationships between pixels, based on flow direction. The focus is on broad categories of global-scale, human-induced pressures. The drivers included are wetland conversion, land-use change and nutrient loading in catchment areas (affecting water quality), and hydrological disturbance and climate change (affecting water quantity). The biodiversity model is based on a recompilation (meta-analysis) of existing data, thereby scaling-up from local/regional case studies to global trends.

Figure 1 gives a schematic view of the model chain. Input and output (indicator) variables are listed in Table 2 and clarified below.

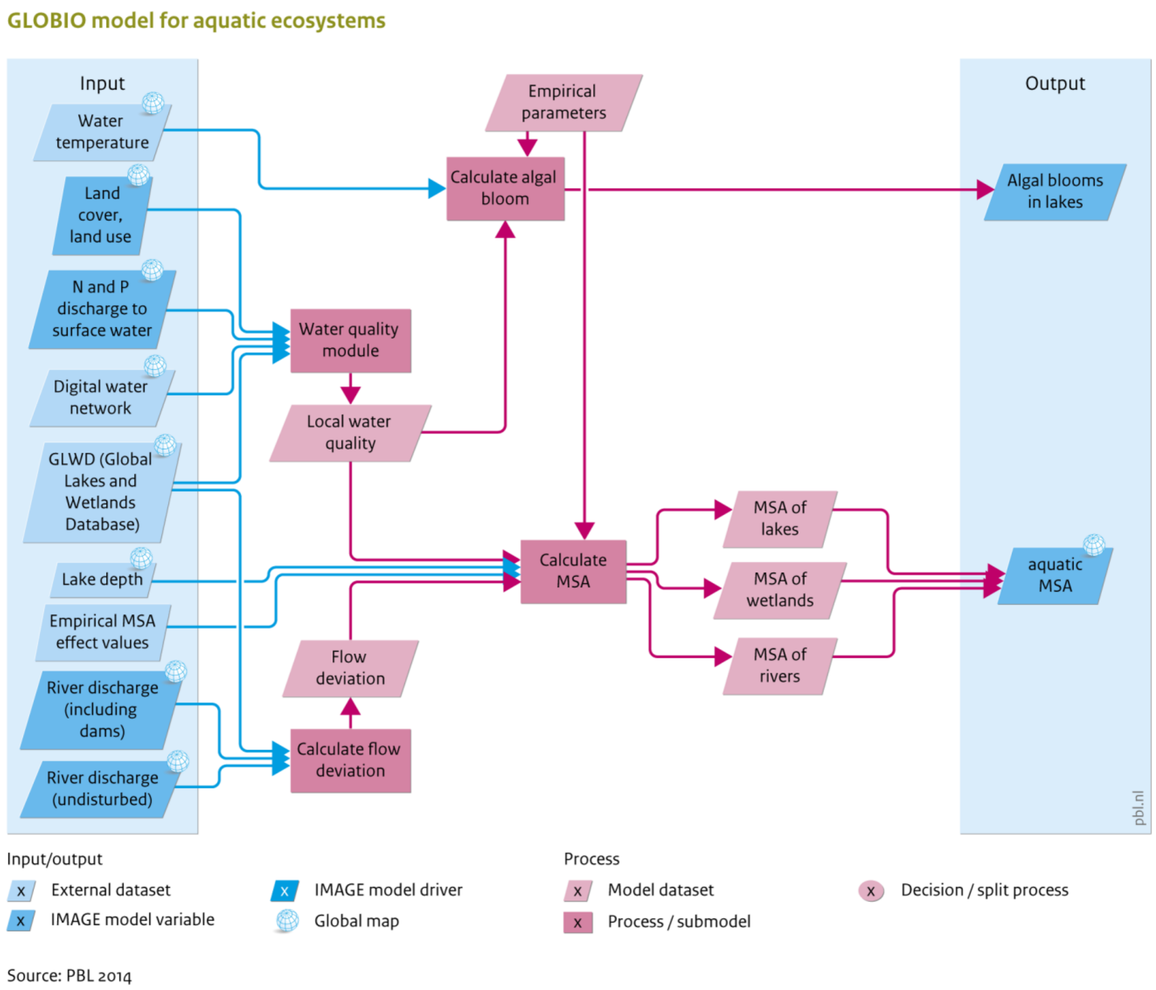


Figure 1. Schematic representation of the GLOBIO-Aquatic model: input data (left, blue), model calculations (centre, red) and output data (right, blue). Parallelograms denote variables or data sets derived from other IMAGE modules (dark blue) or external sources (light blue); rectangles denote processes or calculation steps.

Table 2. Overview of input and output data

Input (dimension)	Explanation	Source	Remarks
STATIC INPUT MAPS			
Map of surface waters (lakes, rivers, wetlands)	To identify locations and types of aquatic ecosystems	Global Lakes and Wetlands Database (GLWD), Lehner and Döll (2004)	30’ raster map, aggregated from GLWD-level 3 (= 30” raster)
Lake depths (m)	Some of the biodiversity effects depend on water depth	FLAKE database, Kourzeneva (2010)	Locations (IDs) attributed to 30’ pixels
Digital water network (LDD map)	To calculate water movement across the globe (through the catchment areas)	Included in PCR-GLOBWB and LPJmL-hydrology	DDM30 (30’ raster)
DYNAMIC INPUT MAPS (DRIVERS)			
Land-use and land-cover map	Driver of change	Land-use module GLOBIO 3.5 (PBL, 2016)	30’’ raster map aggregated to 30’
Map of major river dams	Driver of change	GRanD database (Lehner et al., 2011); included in PCR-GLOBWB and LPJmL-hydrology. Changes/additions in scenarios.	Locations attributed to 30’ pixels
Water discharge (m^3 $month^{-1}$)	Basic driver. Also used to calculate the river flow deviation	PCR-GLOBWB or LPJmL-hydrology	30’ raster, monthly data
Water discharge in natural situation (m^3 $month^{-1}$)	To calculate the river flow deviation, one of the drivers of change	PCR-GLOBWB or LPJmL-hydrology	30’ raster, monthly data
Phosphorus concentration in surface water (g P m^{-3})	Driver of change	Global Nutrient Model (GNM)	30’ raster, year-averages
Nitrogen concentration in surface water (g N m^{-3})	Driver of change	Global Nutrient Model (GNM)	30’ raster, year-averages
Water temperature (ºC)	Driver of change	PCR-GLOBWB	30’ raster, monthly data
OUTPUT MAPS			
MSA map: mean relative abundance of original species in lakes, rivers and wetlands and the weighted average (-)	Measure of biodiversity intactness	Final output	30’ raster maps per water type
Concentration of harmful algae in lakes (g m^{-3})	Algal blooms reduce the usability of the water bodies for several purposes	Final output	30’ raster map for pixels containing lakes

Input data

The model analyses are based on the SSP2 ('middle of the road') scenario combined with the RCP8.5 climate pathway, for the 2010–2050 period. This climate pathway is generally considered too extreme (it is more in line with the SSP3 scenario); however, the more realistic pathways 4.5 and 6.0 were not yet available at the time of this study. Nevertheless, the analysis provides an indication of future impacts.

The locations and types of water bodies were based on the publicly available Global Lakes and Wetlands Database map (Lehner and Döll, 2004). Although the map is mainly based on data from the 1990s, it is the most recent comprehensive map for wetlands. It distinguishes the main inland water types (lakes, reservoirs and rivers) as well as several types of wetlands, namely riverine marshes and swamps, isolated wetlands (bogs and fens), intermediate, brackish and coastal wetlands as well as wetland mosaics.

We modelled the effects of land-use changes on the biodiversity in the catchment areas of all these types of water bodies. For wetlands, we also considered any direct effects, such as due to their conversion or draining for human purposes. For lakes, we used the data on the nutrient loading within their catchment areas, instead of on the land-use itself. For rivers and floodplain wetlands, the model also describes the effect of human interventions in the hydrology (e.g. dam constructions or climate change) on biodiversity.

As wetlands, as yet, are not specifically included in the IMAGE land-use allocation maps (Van Asselen et al., 2013), we used conservative estimations of wetland conversion ('unavoidable wetland loss'), which is to say, the wetland area minimally required to meet the projected increase in agricultural land demand after all non-wetland areas (such as forests) have been used. This is therefore most probably an underestimation.

The effects of land-use change in the catchment areas were based on land-use projections, derived from projections of human population sizes, economic growth, food and energy requirements, and food trade as derived from the IMAGE model (Stehfest et al., 2014), and processed into a 30 x 30 arc-minutes fractional land-use map (Alkemade et al., 2009; PBL, 2016). We used the sum of all human land-use categories (cropland, pastures and urban areas) per grid cell, and combined this with the catchment delineation (derived from the water network) to calculate the human land-use fraction in the upstream catchment. In this way, the *catchment approach* was implemented, with the biodiversity impacts on a certain water body depending on the aggregated land use, and/or accumulated nutrients, from the applicable upstream part of its catchment (watershed). For lakes, rivers, and wetlands connected to rivers, their catchment area was defined as the current pixel plus all upstream pixels, whereas, for the 'isolated' wetland types, their catchment area was confined to the pixel in which they would be located. Data from studies on biodiversity in rivers and streams in catchment and sub-catchment areas with different forms of land use (e.g. forest, agriculture, urbanisation) were combined in a meta-analysis; the data were expressed in the form of MSA and fitted by linear regression (Weijters et al., 2009). A comparable meta-analysis was performed for wetlands.

For lakes, the analysis was based on phosphorus and nitrogen loading rather than on land use, as the eutrophication effects on lakes are well established, and nutrient loading to surface waters, in general, highly correlates with the type and intensity of land use (e.g. Harper, 1992; Johnes et al., 1996). The model considers nutrient loading (nitrogen and phosphorus) from all emission sources—agricultural, urban and atmospheric. The diffuse emissions were calculated using the Global Nutrient Model (Beusen et al., 2015), which translates the land-use practices into soil nutrient budgets (Bouwman et al., 2011) and nutrient leaching and run-off to surface waters. Input data were agricultural area, the application of fertiliser and manure, precipitation and spatial characteristics of slope, soil texture and groundwater characteristics. The urban nutrient emissions were added to these emissions, which were based on human population, affluence (GDP), sanitation and the use of detergents (Morée et al., 2013; Van Drecht et al., 2009). Retention of nutrients within the global surface water network was included, based on slope and retention time. Water discharge was calculated using the global hydrological model PCR-GLOBWB, based on a water balance per pixel (Van Beek et al., 2011; Van Beek and Bierkens, 2009). All fluxes accumulate downstream according to an incorporated water routing routine based on the so-called LDD ('local drain direction') approach (Döll and Lehner, 2002). Lake depths, when available, derived from the FLAKE data set (Kourzeneva, 2010) or otherwise estimated, based on regional characteristics. Literature data on the relationship between biodiversity and P and N concentrations were combined and fitted by logistic regression, for both deep and shallow lakes (Janse et al., 2015).

For rivers and riverine wetlands, GLOBIO also considers the effect of hydrological changes on biodiversity (environmental flow requirements). Monthly river discharges, both in pristine, present and future situations (affected by climate change, river dams and/or water abstraction), were derived from the hydrological module of the LPJ model (Biemans et al., 2011). The so-called 'amended annual proportional flow deviation' (AAPFD), which measures the deviation between affected and natural seasonal patterns (Ladson and White, 1999), was calculated on the basis of these monthly discharge patterns. Data on existing river dams were taken from the GRanD database (Lehner et al., 2011), which contains the ~7000 largest dams in the world. A projection of future hydropower dams was made by Fekete et al. (2010). Future water abstraction and construction of reservoirs for irrigation purposes were taken from Biemans et al. (2017), as described in the document 'Global water and land constraints to food production'. Literature data on river biodiversity under various degrees of regulation (e.g. by dams) were combined and expressed in change in MSA (Janse et al., 2015). A comparable analysis was performed of the effects of flow deviation on biodiversity in riverine wetlands (Kuiper et al., 2014).

Output indicator 1: Biodiversity intactness (Mean Relative Abundance of original species (MSA))

The model expresses the biodiversity response in MSA—the biodiversity intactness index—the same method as is used by a comparable model for terrestrial biodiversity (Alkemade et al., 2009). The relationship between drivers and MSA is described by a set of empirical functions based on meta-analyses of literature data, per driver and water type (Janse et al., 2015; Janse et al., 2016). Data were extracted from studies comparing the species composition in undisturbed reference situations with those at different levels of the driver (for naturally comparable water types). In principle, the abundance (numbers, density, cover percentage) of each species found in an impacted situation was divided by its abundance found in an undisturbed reference situation. The values were truncated at 1.0, and a mean value was calculated over all species considered in the study. Species not found in the undisturbed situation were omitted. In case only the IBI values (= Index of Biotic Integrity; Karr and Chu, 2000) were reported instead of the raw data, these were converted into MSA values by rescaling them between 0 and 1.

The combined MSA value per water body was calculated by multiplying the impact factors for the relevant drivers (hence assuming that the drivers would be independent). The final indicator 'aquatic MSA' was then calculated by area-weighted averaging of the MSA values for rivers, lakes and wetlands.

Output indicator 2: Harmful algae

The amount of harmful algae (cyanobacteria) in lakes was calculated by the empirical relationship, derived by Håkanson et al. (2007). According to this relation, the amount of cyanobacteria increases with the phosphorus concentration, and is further increased if the N:P ratio is low (i.e. below 15), and increases with the average water temperature in the growing season. The P and N concentrations were derived from the GNM model (see the document on 'Nutrients and water quality'); the water temperature was calculated with the PCR-GLOBWB model (Van Beek et al., 2012).

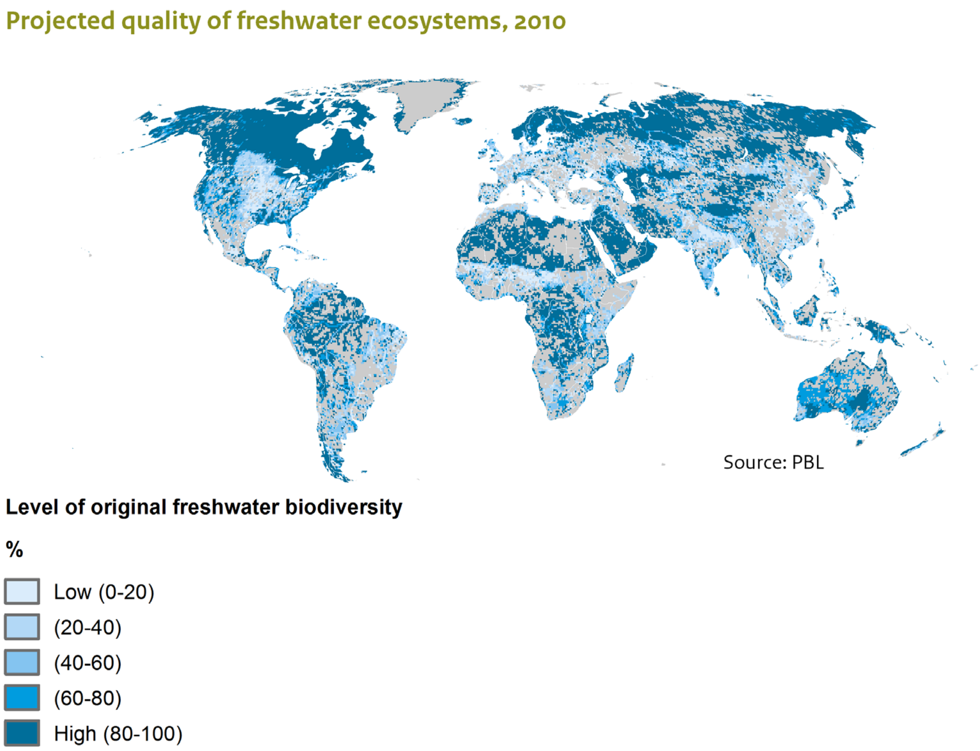
1.1.4 Results

Results are given for aquatic biodiversity intactness (MSA) and harmful algal blooms. Focus is on the situation in 2010 and in 2050, the difference between those years, and the causes of change.

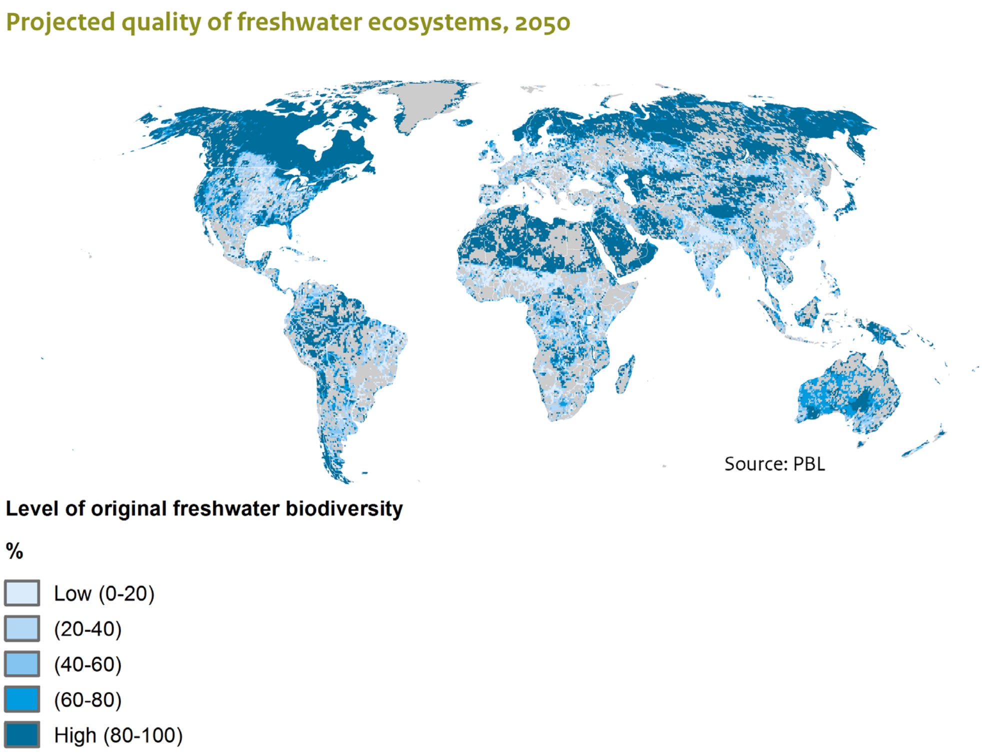
Aquatic biodiversity intactness (MSA)

The maps in Figure 2 show the average area-weighted biodiversity intactness (MSA) for aquatic ecosystems (rivers, lakes and wetlands) on a 30 x 30 arc minutes grid scale. Pixels without aquatic ecosystems according to the GLWD (Lehner and Döll, 2004) are presented in white.

A: Situation 2010



B: Situation 2050



C: Change 2010–2050

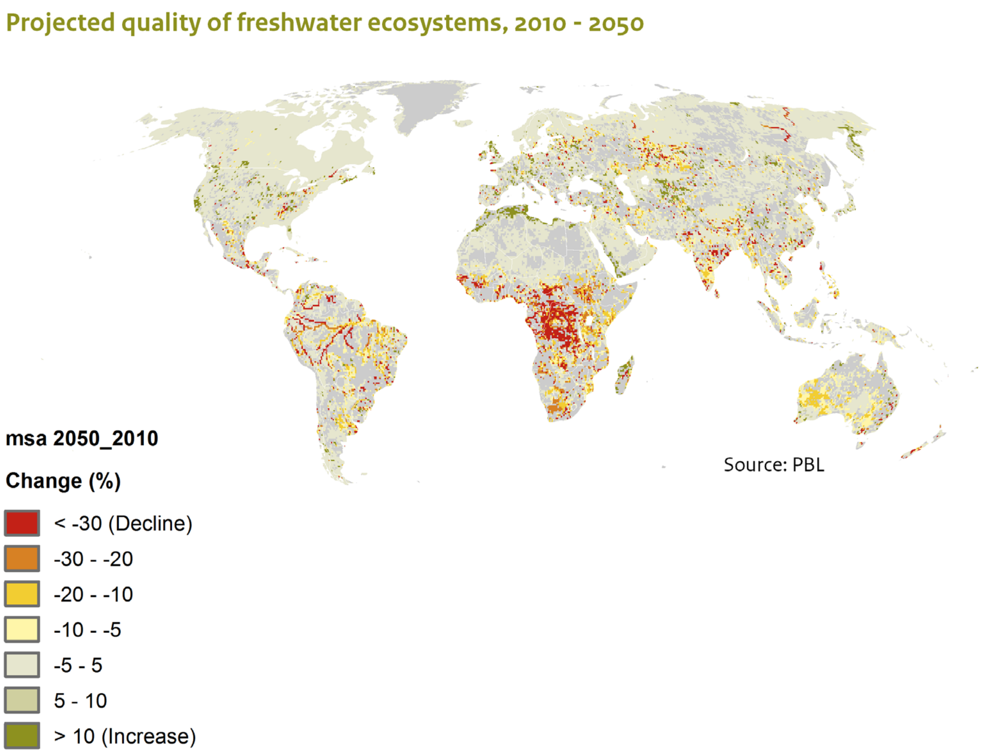


Figure 2. Aquatic biodiversity, measured by the biodiversity intactness indicator (MSA), for the world's freshwater systems in 2010 (A) and 2050 (B), and for the change from 2010 to 2050 (C). Figures A and B: scale varies from dark blue (MSA 1: biodiversity not affected by human drivers) to light blue (MSA = 0: biodiversity completely affected by human drivers). Figure C: red–orange–yellow = biodiversity loss; grey = biodiversity remains almost stable; green = biodiversity increases).

According to the results in Figure 2, in many parts of the world, aquatic biodiversity had already declined considerably in 2010, especially in western, central and southern Europe, the United States/Mexico, southern, eastern and parts of central Asia, the southern Sahel and parts of South Africa, Argentina and Brazil. Loss of aquatic biodiversity is much less in northern Europe, Canada, northern Russia, Australia, central Africa and large parts of South America. In general, the boreal biome is the least-affected, and the populated temperate, Mediterranean and subtropical biomes are affected the most. The world averaged aquatic MSA (the average for all pixels with water bodies) has decreased to about 0.75; about three quarters of the decline can be attributed, directly or indirectly, to land-use changes. As expected, the largest impacts appear in the most densely populated and the most cultivated world regions. Rivers and floodplain wetlands are affected in some of the less populated catchments as a consequence of damming.

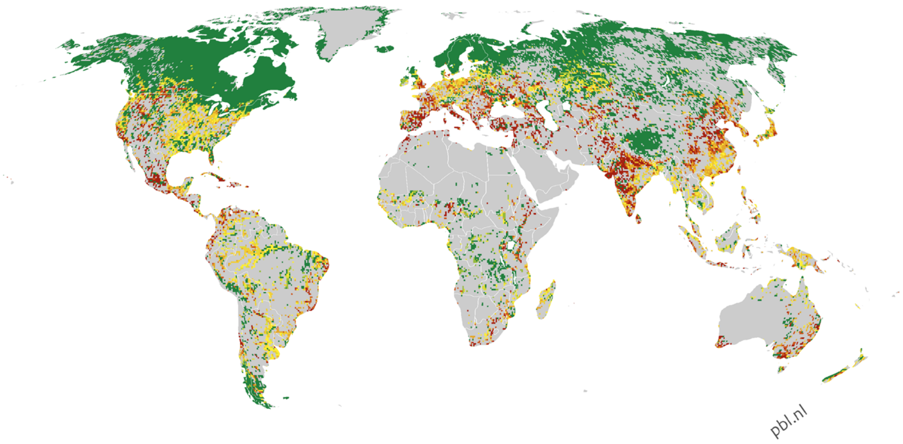
Under the SSP2 scenario, a further decline in aquatic biodiversity is expected for the future. The scenario projects a major decline for Africa, in line with projected changes in land use and increased dam construction. Further decline is also projected for Asia, Latin America and eastern Europe. Some improvement is projected for parts of the United States, Europe, the north-west African coastal region and in parts of central Asia, due to an assumed decrease in agricultural area and/or as a result of eutrophication abatement.

Harmful algal blooms in lakes

The maps in Figure 3 depict projected average concentrations of cyanobacteria (potentially toxic algae) in lakes, during the growing season [mg/l]. Green colours denote concentrations lower than the WHO standard, yellow and red colours point to increasing levels of exceedance. Pixels without lakes, according to the GLWD (Lehner and Döll, 2004), are shown in white.

A: Situation 2010

Harmfull algal bloom in lakes, 2010

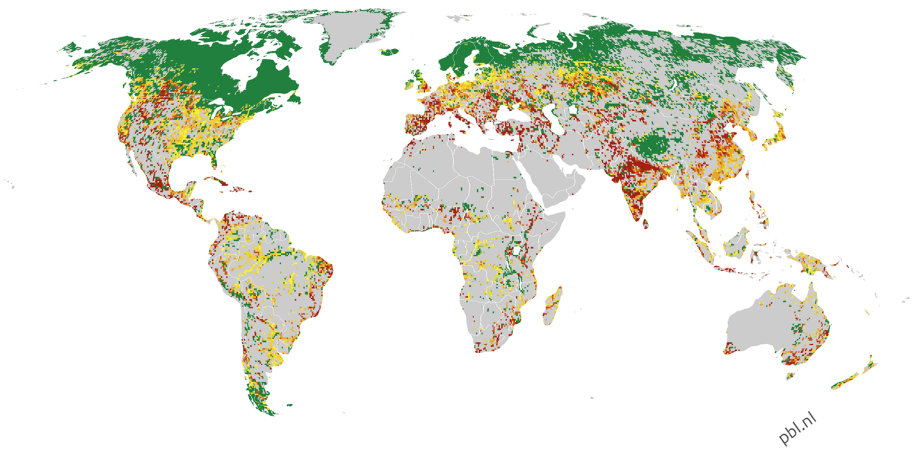


Average concentration of cyanobacteria (mg/l)

0 - 0.7	1.4 - 2.8	5.6 - 11.2	22.4 - 44.8
0.7 - 1.4	2.8 - 5.6	11.2 - 22.4	> 44.8

B: Situation 2050

Harmfull algal bloom in lakes, 2050



Average concentration of cyanobacteria (mg/l)

0 - 0.7	1.4 - 2.8	5.6 - 11.2	22.4 - 44.8
0.7 - 1.4	2.8 - 5.6	11.2 - 22.4	> 44.8

C: Change 2010–2050

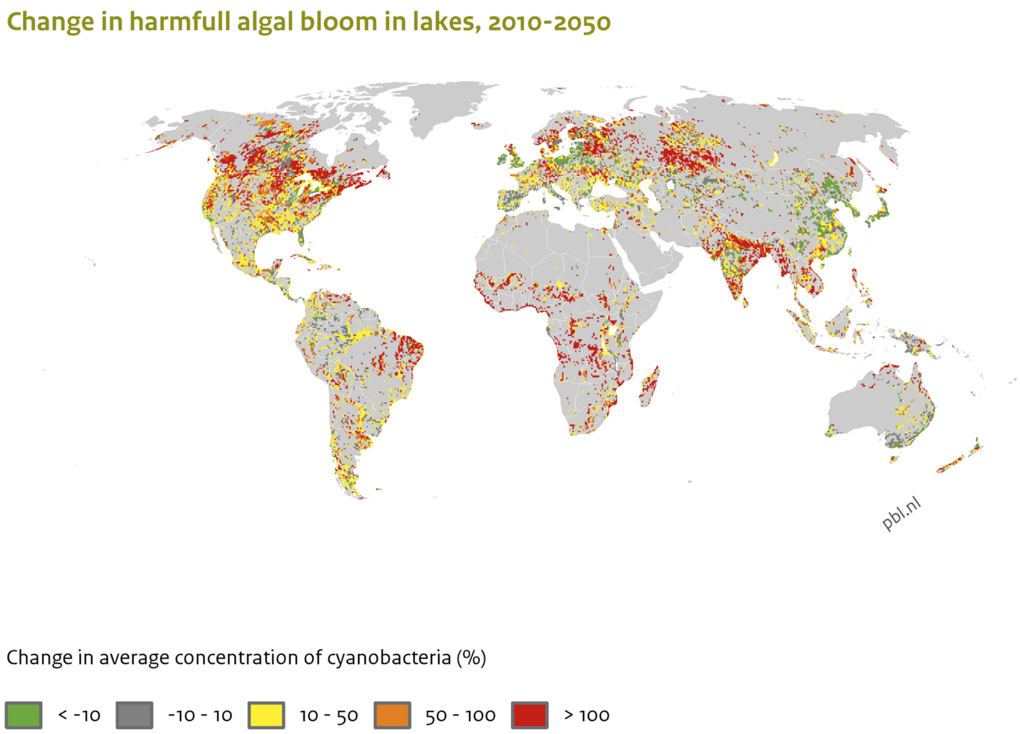


Figure 3. Projected average concentration levels of cyanobacteria in lakes, during the growing season, in 2010 (A) and in 2050 (B), and the change from 2010 to 2050 (C) under a combination of the SSP2 and RCP8.5 scenario. Figures A and B: the scale varies from dark green (no cyanobacteria) to light green (concentration lower than WHO standard) and yellow (concentration exceeds WHO standard) to red (concentration ≥50 mg/l). Figure C: red–orange–yellow = concentration increases; grey = concentration remains almost stable; green = concentration decreases).

The highest algal concentration levels are projected for the most populated and/or intensively farmed agricultural regions, such as Europe and western Asia, the United States/Mexico, South Asia, eastern China and eastern Brazil. Low concentration levels are projected for the boreal biome (due to a combination of low water temperatures and low population density) and for regions that are either less populated, have little intensive agriculture, and/or a good wastewater treatment system. These are parts of the United States, South America, central Africa and parts of Asia.

Under the SSP2 scenario in combination with the RCP8.5 climate scenario, a striking increase in harmful algal blooms is foreseen for 2050, in many parts of the world, except for the far north. In parts of Europe and the United States, some decreases are projected as a result of emission reductions. WHO standards will be exceeded in more regions, and the increased risk of toxic algal blooms will further hamper the use of water resources for drinking water, fish farming, and recreation. The increase is due to increased nutrient emissions from agriculture as well as urban sources (see the document ‘Water Quality’), combined with a global increase in water temperature that promotes algal growth and cyanobacteria, in particular (Moss et al., 2011).

To disentangle the impacts from each factors, the 2050 model run was repeated, changing one driver at a time. When only temperature increase is ‘switched on’ (and land-use changes are ignored), cyanobacteria are still expected to increase in most regions, but to a lesser extent.

1.1.5 Discussion

Uncertainties / Restrictions

The projections in this document should be interpreted with some caution, because of many uncertainties in the assumptions by the underlying models. Also, the meta-analyses, in general, were based on only a limited amount of data, and mostly confounded to data from the 'developed' parts of the world. The projected aquatic biodiversity losses of wetlands are very likely to have been underestimated, as historical wetland conversions (60-70% in the 20th century; Davidson, 2014) are not accounted for in the calculations, and future conversions only as a minimum estimate (Janse et al., 2015; Janse et al., 2016), while current annual rates of wetland losses of 0.5% to 1% are observed (Dixon et al., 2016; Gardner et al., 2015) These shortcomings will be addressed in a future update of both models and data. Projections of cyanobacterial biomass have been estimated with an empirical regression model that was largely based on a data set on lakes in northern regions, under temperate climate conditions. In addition, a more elaborate module, based on PCLakePlus (Janssen et al., 2019, will also be implemented in the future. Furthermore, a module about the impact of climate change on the distribution range of aquatic species is being developed.

How do the results relate to those from other relevant studies?

According to the IPCC, direct human impacts, such as land use and land-use change, pollution and water resource development, will continue to dominate the threats to most freshwater (high confidence) and terrestrial (medium confidence) ecosystems, globally, over the next three decades. Ecosystem changes resulting from climate change may not become fully apparent for several decades, due to long response times in ecological systems (medium confidence) (IPCC, 2014).

Our modelling study confirms the dominant impact of land-use changes and hydrological interventions on freshwater systems, both currently and up to 2050. These are already being affected by climate change (see also the documents on 'Nutrients and water quality', 'Global water and land constraints to food production' and 'Hydropower and water'), but the extent of the impact of course highly depends on the assumed climate change scenario. Our results show that, at least for the 'high' RCP8.5 scenario, global warming is expected to increase algal bloom problems as early as in the coming decades, on top of the impact of the increasing nutrient emissions from agricultural and urban sources. This matches the observed rapid warming of lakes, worldwide (on average, 0.34 °C per decade; O'Reilly et al., 2015) and with observational and theoretical studies showing an increase in algal blooms (especially cyanobacteria) in warmer years (Jeppesen et al., 2014; Moss et al., 2011).

The impact of warming on lakes, however, depends on local characteristics and food web interactions—oligotrophic large lakes (with a chlorophyll-a concentration < 3 mg m^{-3}), for instance, even show a decrease in algal concentration in warm years (Kraemer et al., 2017). The interaction between eutrophication and climate change offers both challenges and opportunities for regional water management. One may argue that the positive effects of improved local water management are nullified by climate change. On the other hand, adaptive land and water management can sometimes compensate the effects of climate change (Green et al., 2017).

The presented map of aquatic biodiversity loss between 2010 and 2050, based on the MSA indicator (Figure 2C), overall, matches the map of threats, derived by Vorosmarty et al. (2010), rather well. In an additional step, this map of biodiversity loss was combined with the map of fish species richness by Tisseuil et al. (2013). The size of the blue dots denotes the number of species per river basin. Especially the Congo basin (central Africa) shows up as a potential hotspot of species loss. Also, the Amazon and Mekong are species-rich basins where the expected loss of aquatic biodiversity in rivers is relatively high.

The areas with the highest levels of aquatic biodiversity loss are often inadequately covered by the existing network of protected areas (as mapped in the WDPA (UNEP-WCMC 2017), even those in the 'Ramsar list of wetlands of international importance' (Reis et al., 2017)). This is partly due to the fact that the water quality downstream depends on the quality upstream, and this relationship is often neglected during the design of these networks.

As shown, part of the decline in aquatic biodiversity in rivers and floodplain wetlands is due to hydrological disturbance caused by the damming of rivers, for water storage or hydropower purposes. In 2005, 59% of the world's large river systems (covering 88% of the area and 83% of the mean annual discharge) were highly or moderately fragmented (Nilsson et al., 2005). Especially in some boreal and tropical biomes there are still unfragmented rivers left.. The increase in dam construction, as projected under the Trend scenario, will increase river fragmentation, also in currently hardly fragmented river basins in the tropics, and will compromise the environmental flow requirements for these river systems (see also the document on 'Hydropower and water'). The current projection is based on the irrigation scenario by Biemans et al. (2017) and the hydropower potential described by Fekete et al. (2010). More recent hydropower scenarios (Zarfl et al., 2015; Gernaat et al., 2017) project a comparable increase in total global hydropower capacity, although somewhat differently distributed across the globe.

Adaptive capacities

As summarised by Boelée et al. (2017), and also concluded by many others, there are still ample opportunities (1) to reduce the negative impacts of projected developments on aquatic ecosystems, by strategies that minimize trade-offs between various goals, and (2) to create synergies between ecological systems and society by substantially increasing the use of nature-based solutions in solving future water problems (WWAP, 2015; Ozment et al., 2015). The current international dialogue on the nexus between water, energy and food may raise awareness about the need for integrated solutions (Krchnak et al., 2011). These include opportunities in agricultural water management, urban water management, river basin management and flood protection, including the following:

- The conservation or restoration of wetlands may increase their resilience to flooding and drought, and help to improve water quality.
- An increased reuse of water and nutrients may reduce the level of scarcity of these resources and reduce pressures on aquatic ecosystems; improved land-use practices would do the same.
- Finding alternative ways of balancing hydro-energy use and other functions of rivers in integrated river management plans may help to maintain environmental flow conditions. Successful implementation of such 'nature-inclusive' solutions calls for technical and ecological knowledge, as well as institutional and societal changes, if those are to solve the world's water-related problems.

1.1.6 Conclusions

Aquatic biodiversity, already under great pressure, is likely to further decrease in the future, in many regions, due to additional land-use change and hydrological disturbance. The risk of harmful algal blooms in lakes will increase, hampering the ecosystem services that they provide.

1.1.7 Gaps and recommendations for future research

The shortcomings, as described above, in the model assumptions and the limited availability of data will be addressed in a future update of both models and data. A more elaborate module to project future cyanobacterial biomass, based on PCLakePlus (Janssen et al., 2017), will also be implemented in the future. Furthermore, a module about the impact of climate change on the distribution range of aquatic species is being developed.

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