



PBL Netherlands Environmental  
Assessment Agency

# GLOBIO-AQUATIC

## Technical Model Description

Model version 1.3 (Aug. 2014)

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**September 2016**

PBL

## **Colophon**

### **GLOBIO-Aquatic Technical Model Description**

PBL Netherlands Environmental Assessment Agency

The Hague, 2016

PBL publication number: 2829

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### **Editing and production**

PBL Publishers

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# 1 Introduction

The GLOBIO-Aquatic model (Janse et al., 2015) describes the effects of human-induced changes to the environment on the biodiversity of freshwater ecosystems. These systems (inland waters, including rivers, natural lakes, reservoirs and wetlands) now cover about 8-9 % of the earth's continental surface (Lehner and Döll, 2004), while at least some 15% in the past (estimated from Davidson, 2014). Because of the specific nature of freshwater systems (*i.e.* dynamically linked elements in the global hydrological cycle), and because the drivers of biodiversity loss are partly different from those of terrestrial ecosystems, they are covered in a separate model, complementing the GLOBIO model for terrestrial systems (Alkemade et al., 2009). GLOBIO-Aquatic covers wetlands conversion (the 'areal aspect') and effects on biodiversity (the 'quality aspect') of major anthropogenic pressures. The focus is on broad categories of human-induced pressures that still hold when scaled up from a local/regional level to the global level. Currently (in v. 1.3) the drivers *land-use change* (including the associated *eutrophication*), *hydrological disturbance* and *climate change* are included (Janse et al., 2015).

Although the terrestrial and aquatic GLOBIO models use the same land-use and climate data, there are some important differences in the way these data are used. The main difference is that water is moving, and thereby creates spatial linkages. The aquatic model is therefore based on the *catchment approach*, *i.e.* the biodiversity impacts on a certain water body depend on the *aggregated* land-use and/or the accumulated nutrients from the applicable upstream part of its catchment (watershed), whereas the terrestrial model always uses the *local* land use only. A second difference is that the aquatic model uses nutrient loadings (nitrogen and phosphorus) from all emission sources (agricultural, urban and atmospheric), whereas the terrestrial model uses only input by atmospheric nitrogen. Moreover, the hydrological effects of climate change, water use and river dams are a special feature of the aquatic model, as are the impacts of roads in the terrestrial model. Like in the terrestrial model, the biodiversity response is expressed as a biodiversity intactness index (called MSA, 'Mean Species Abundance of original species'), and the driver-impact-relationships are based on meta-analyses of empirical data from literature. In addition, the model calculates the occurrence of harmful algal blooms in lakes, because of its generally negative correlation with biodiversity, water quality and a number of ecosystem services. The model is embedded in the IMAGE model framework for land use and global environmental change (Stehfest et al., 2014).

This report is restricted to a **technical description** of the model, v. 1.3 (Aug. 2014), as an addition to the paper by Janse et al. (2015), where a more elaborate explanation of the model's functionality, rationale and a critical discussion can be found.

The following sections describe the overall model structure and elements (section 2), the included drivers (section 3), the biodiversity responses in rivers, wetlands and lakes (sections 4-6), the algal bloom response in lakes (section 7) and the aggregation procedure (section 8).

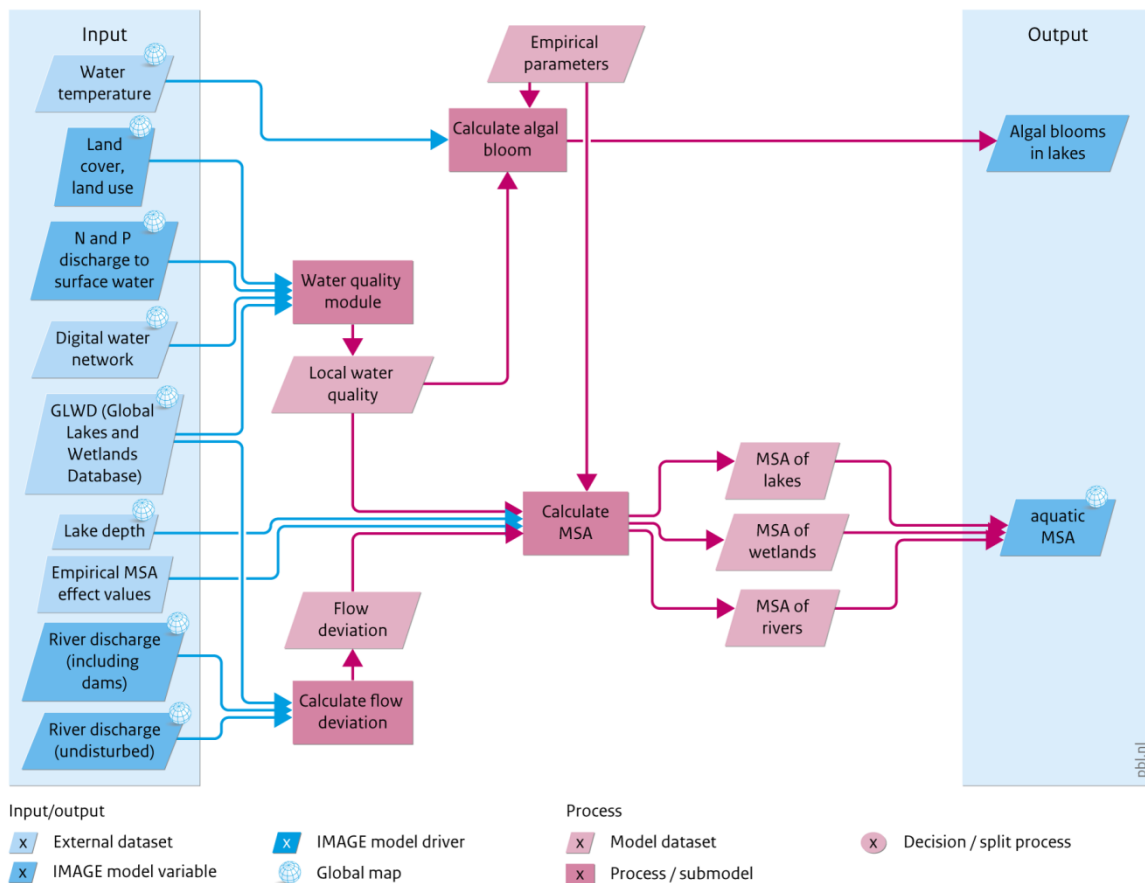
# 2 Modelling approach

## 2.1 Model structure and elements

### 2.1.1 Overview

The aquatic model chain consists of a land use and climate change model, a hydrological model, a nutrient model, a map of the water bodies and a set of empirical relations between drivers and biodiversity intactness as well as algal blooms. The catchment approach is applied by including the spatial relations between pixels, based on flow direction. Figure 1 shows schematically the relationships between the models for the drivers currently addressed. The input and output data are summarized in Table 1. The input data comprise a number of (static) input maps (further explained in this section) and a number of (dynamic) drivers, explained in section 3.

**GLOBIO model for aquatic ecosystems**

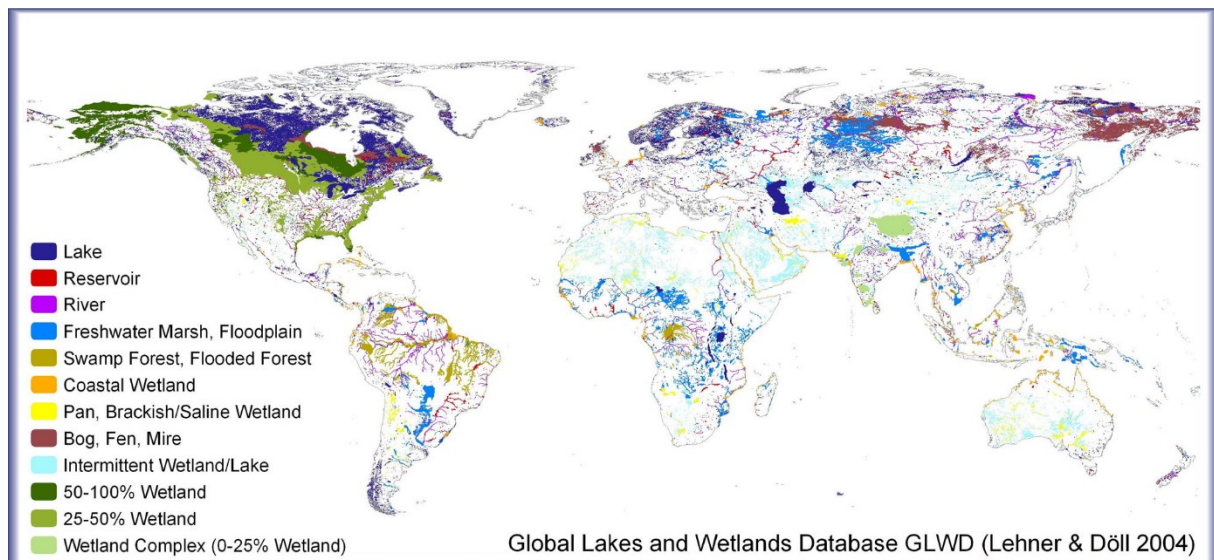


Source: PBL 2014

**Fig. 1. Schematic representation of GLOBIO-Aquatic: 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 (light blue); rectangles denote processes or calculation steps.**

**Table 1. Overview of input and output data**

<b>Input (dimension)</b>	<b>Purpose</b>	<b>Source</b>	<b>Remarks</b>
<b>STATIC INPUT MAPS</b>			
Map of surface water bodies (lakes, rivers, wetlands)	Location 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 are dependent on water depth	FLAKE database, Kourzeneva (2010)	Locations (IDs) attributed to 30' pixels
Digital water network (LDD map)	To calculate the movement of the water across the globe (through the catchment areas)	Included in PCR-GLOBWB and LPJmL-hydrology	DDM30 (30' raster)
<b>DYNAMIC INPUT MAPS (DRIVERS)</b>			
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 <sup>3</sup> month <sup>-1</sup> )	Basic driver, also to calculate the river flow deviation	PCR-GLOBWB or LPJmL-hydrology	30' raster, monthly data
Water discharge in natural situation (m <sup>3</sup> month <sup>-1</sup> )	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 <sup>-3</sup> )	Driver of change	Global Nutrient Model (GNM)	30' raster, year-averages
Nitrogen concentration in surface water (g N m <sup>-3</sup> )	Driver of change	Global Nutrient Model (GNM)	30' raster, year-averages
Water temperature (°C)	Driver of change	PCR-GLOBWB	30' raster, monthly data
<b>OUTPUT MAPS</b>			
Relative Mean Species Abundance (MSA) 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 <sup>-3</sup> )	Algal blooms reduce the usability of the water bodies for several purposes	Final output	30' raster map for pixels containing lakes



**Fig. 2. Global Lakes and Wetlands map (GLWD) (Lehner and Döll, 2004)**

### 2.1.2 Location and type of water bodies

The location and type of the water bodies, being the central subject of the model, are based on the publicly available Global Lakes and Wetlands Database map (Lehner and Doll, 2004) (Fig. 2). This map 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 etc.), intermediate, brackish and coastal wetlands as well as wetland mosaics (Table 2). The GLWD partly draws upon previous maps and information; the data sources are varied but mainly date from the 1990s. The dataset consists of three levels, level 1 and 2 comprising polygons of all ~250,000 water bodies (lakes, reservoirs and river stretches) with an area over 0.1 km<sup>2</sup>, whereas level 3 is a raster map at a 30 arc second resolution. From the GLWD-3 the fractional area of each type of surface water in each grid cell (currently 30x30 arc minutes) is calculated (again as a raster map) for use in GLOBIO. For the 'mosaic' categories 10, 11 and 12, fractions of 1.0, 0.15 and 0.125 were used, respectively, following Lehner and Döll (2004) (*i.e.* category 10 is eventually not regarded as a mosaic but as 100% wetland).

**Table 2. Classification and global area of water bodies (GLWD, 2004)**

ID	Class	Global area	
		10 <sup>3</sup> km <sup>2</sup>	% <sup>1</sup>
1	Lake	2428	1.8
2	Reservoir	251	0.2
3	River	360	0.3
4	Freshwater Marsh, Floodplain	2529	1.9
5	Swamp Forest, Flooded Forest	1165	0.9
6	Coastal Wetland	660	0.5
7	Pan, Brackish/Saline Wetland	435	0.3
8	Bog, Fen, Mire	708	0.5
9	Intermittent Wetland/Lake	690	0.5
10	50-100% Wetland <sup>2</sup>	882-1764	0.7-1.3
11	25-50% Wetland <sup>3</sup>	790-1580	0.6-1.2
12	Wetland Complex (0-25%)	0-228	0-0.2
Total lakes and reservoirs (classes 1 and 2)		2679	2
Total rivers and wetlands (classes 3-12)		8219-10119	6.2-7.6

<sup>1</sup> of continental surface (excl. Antarctica and Greenland)

<sup>2</sup> taken as 100% wetland

<sup>3</sup> taken as 15% wetland

### 2.1.3 Water depths

Data on the depth of lakes and reservoirs are (if available) derived from the 'FLAKE' dataset (Kourzeneva, 2010). FLAKE contains depth data for over 8000 lakes and reservoirs (out of the over 29000 grid cells where lakes exist according to the GLWD). Lakes are divided into the categories 'shallow' and 'deep' based on a boundary value of 3 m mean depth (because the biodiversity relations differ; see section 6). In case of multiple values within a cell, a frequency distribution of these categories is calculated. Missing values are estimated by (in this order): a) the elevation map: lakes in mountainous regions are assumed to be deep; b) expert judgment based on regional characteristics; c) nearest neighbour (only within a biome); and d) the world average (this last option is needed very little). Depth data on rivers and wetlands are not needed for the model and not included.

### 2.1.4 Water network (LDD map)

The water network forms the connection between the water bodies (GLWD map) and the drivers, by linking the water flow and nutrient loadings to the water bodies. Water discharge is calculated by the global hydrological model PCR-GLOBWB (Van Beek et al., 2011; Van Beek and Bierkens, 2009) and/or the hydrological module of the global vegetation model LPJmL (Biemans et al., 2011). (Recent GLOBIO applications have used the first model for the driver eutrophication and the second one for hydrological disturbance by dams.) The discharge is based on a water balance per pixel, including precipitation, evapotranspiration, snowmelt, infiltration to groundwater and human water abstraction. In these models, the discharge is affected by climatic variables, land use, water abstraction, and by the presence and the way of management of dams and reservoirs. The two models differ in time scale, in the schematization of river floodplains and wetlands and in the definition of vegetation and crop types. Run-off is currently modelled at a spatial resolution of 30x30 arc minutes (approx. 50x50 km at the equator). All fluxes are accumulated downstream according to the water routing routine based on the LDD approach (= local drain direction), which is in its turn based on a digital elevation model (DEM). The current model uses the DDM30 map (*i.e.* 30x30 arc minutes resolution) (Döll and Lehner, 2002). From the resulting flow pattern, the delineation of the river catchments becomes automatically visible.

## 2.2 Biodiversity modules

The indicator for biodiversity intactness (MSA) is based on the same principles as in the terrestrial GLOBIO model (Alkemade et al., 2009; PBL, 2016). In short, the relationship between drivers and MSA is described by a set of empirical functions based on meta-analyses of literature data, per driver and per water type (Janse et al., 2015).

Data are extracted from studies comparing the species composition in undisturbed reference situations with those at different levels of the disturbing driver (for naturally comparable water types). In principle, the abundance (number, density, cover percentage) of each species found in an impacted situation is divided by its abundance found in an undisturbed reference situation. The values are truncated at 1.0, and a mean value is calculated over all species considered in that study. Species not found in the undisturbed situation are omitted.

For studies in which only the IBI values (= Index of Biotic Integrity) were reported instead of the raw data, we transferred these into MSA values by rescaling them between 0 and 1 for the minimum and maximum IBI values adopted in the study, respectively, assuming linear interpolation. So,

$$MSA = \frac{IBI - IBI_{min}}{IBI_{max} - IBI_{min}} \quad (1)$$

(Note: while the original design of the IBI (Karr and Chu, 2000) used a minimum value of 12 and a maximum of 60, in later IBI studies these values may differ.)

If a study reported only the Ecological Quality Ratio (EQR), the EQR was used as a proxy of the MSA.

This technical document is confined to a technical description; all meta-analyses are further explained by Janse et al. (2015), Kuiper et al. (2014) and Weijters et al. (2009). In general, the number of papers suitable for MSA calculations was only limited, and for 80-90% confined to the 'developed' world. Additional data collection is planned for future model improvement.

The following relationships are currently included (table 3):

**Table 3. Driver – water type combinations included in the model (v.1.3)**

Driver	Biodiversity intactness (MSA)						Cyanobact. Lakes (1)
	Lakes (1)	Reserv. (2)	Rivers (3)	Floodplain wetlands & swamps (4,5)	Coastal Wetlands (6)	Isolated Wetlands (7-12)	
Conversion <sup>a</sup>				+	+	+	
Land-use in catchment			+	+	+		
Land-use in current pixel						+	
Accumulated nutrients	+	+	+ <sup>b</sup>				+
Nutrients from current pixel							
Hydrological changes			+	+			
Water temperature							+

<sup>a</sup> affects area (extent)

<sup>b</sup> optional

As the drivers are assumed to be independent of each other, the MSA value (for a certain water type in a certain pixel) is obtained by **multiplication** of the applicable driver factors (if there are more than one) as shown in table 3); details are given in section 8. Aggregation over regions is generally done by area-weighted averaging (see section 8 and Appendix), It is based on the *area* of water bodies (rather than for instance their volume), as areas are the focus of the model, analogous to the terrestrial model.

Complementary to the MSA, the occurrence of harmful algal blooms (primarily cyanobacteria) has been included as an indicator of the ecological status of lakes. Algal blooms are often used as a disturbance indicator, generally negatively related to MSA, as they exclude other native species. This indicator also precludes a link to the aquatic ecosystem services module in development. The algal blooms module is based on the drivers eutrophication (P and N) and climate change in terms of rise in water temperature; see section 7.

## 3 Drivers

### 3.1 Direct land-use change: wetland conversion

Land-use changes have both direct and indirect effects on water bodies. This paragraph deals with the direct effects, *i.e.* the conversion or draining of wetlands for human purposes. (For rivers and lakes, this is left out as it is restricted to some special cases.) The global wetland area has decreased since 1900 by over 60% (Davidson, 2014) and is still decreasing. For instance Prigent et al. (2012) found a 6% loss in a 15 years period (1993-2007), and Dixon et al. (2016) a 30% decline in 38 years (1970-2008). So, the areas reported in the GLWD (from the 1990s) are outdated in some regions. Agricultural expansion is one of the main causes of wetland conversion (e.g. Van Asselen et al., 2013).

As there are currently no historical wetland maps available to derive past wetland conversions, and as wetlands are not specifically covered in the maps from IMAGE or the terrestrial GLOBIO 3.5 model, an indirect method is used. A conservative guess (a minimum estimate of wetland conversion) is made, based on the area of wetlands minimally required to meet the projected increase in agricultural land demand if all non-wetland areas (such as forests) have been used. In case of a crop or pasture 'claim' (from IMAGE) in certain grid cells, this claim is first allocated to the non-wetland natural land cover types in the cell. The area of wetland is derived from the GLWD (classes 4-12), *i.e.* the extent in the 1990s. If the claim is larger than the area of non-wetlands, then wetlands are converted; this is called the unavoidable loss of wetland. Application of this method to the 2000 IMAGE scenario revealed that indeed a part of the GLWD (2004) wetlands is modelled as converted.

We realise that this method has two shortcomings. First, it does not cover historical wetland conversion (*i.e.* before ~1990), which would require historical wetland maps. A draft version of such a map has been produced from calculations with the hydrological model PCR-GLOBWB using only natural input data (Brolsma et al., 2012). Secondly, the 'minimum estimate' of wetland conversion is most probably an underestimation. An improved functionality (in development) will make use of recent data on conversion risk (e.g. Van Asselen et al., 2013), brought in line with conversion rates in the terrestrial model (GLOBIO 3.5).

## 3.2 Land-use change in catchment

Apart from these direct land-use changes, water bodies are often also (indirectly) affected by the land-use changes in their (upstream) catchment, by spatial relations created by the moving of water from high to low places through the landscape.

Projections of land use, based on projections of human population size, economic growth, food and energy requirements and food trade, are derived from the IMAGE model (Stehfest et al., 2014) and processed by the GLOBIO 3.5 model into a 30x30 arc-minutes fractional land-use map (Alkemade et al., 2009; PBL, 2016). The sum of all human land-use categories (agricultural and urban, GLC categories 16 (cropland) + 22 (urban) + 30 (pastures)) per grid cell was taken, and combined with the catchment delineation (derived from the hydrological model and LDD network) to calculate the 'accumulated human land use fraction' per cell (called "FRHLU" in the implemented model), *i.e.* the human land-use fraction of the upstream part of the catchment.

For the water types 1-6 (lakes, rivers, and wetlands connected to rivers), the catchment is defined as the current pixel plus all upstream pixels in the hydrological model, whereas for the 'isolated' wetland types (7-12) the catchment is confined to the 30' pixel in which they are located. This is a crude approximation, to be refined in a future model version.

## 3.3 Nutrient emissions

As shown by numerous studies (*e.g.* Harper, 1992; Johnes et al., 1996; Crosbie and Chow-Fraser, 1999) and also recalled by Janse et al. (2015), the type of land cover and land-use in a catchment is generally well reflected in the nutrient concentrations in the receiving water bodies. Nutrient levels also reflect the *intensity* of human land-use in the catchment (*e.g.* the level of manure and fertilizer use for agriculture, and the amount of pollution from urban sources). Hence, nutrient levels can be used as an additional (and more sensitive) indicator for the effects of catchment land-use on water bodies.

For the agricultural land (cropland and pastures), the Global Nutrient Model (Beusen, 2015) translates the land-use practices into soil nutrient budgets (Bouwman et al., 2011) and nutrient loadings to aquatic systems from diffuse sources. Nitrogen and phosphorus leaching and runoff from the land to the surface waters is modelled based on agricultural area, the application of fertilizer and manure, precipitation and spatial characteristics of slope, soil texture and groundwater characteristics. To these emissions are added the urban nutrient emissions, modelled based on population, affluence (GDP), sanitation and the use of detergents (Morée et al., 2013; Van Drecht et al., 2009). Retention of nutrients in the global surface water network is included, based on slope and retention time.

GLOBIO-Aquatic uses the accumulated total N and P concentrations as the driver for lakes, and optionally also for rivers (besides land-use as the default option). For wetlands nutrients were not used, due to data limitations in the biodiversity studies.

### 3.4 Hydrological disturbance

Hydrological disturbance is defined here as a deviation of the current river flow from the natural ('undisturbed') one. Deviations may result from several causes:

climate change (change in rainfall or evaporation);

water abstraction;

river dams, for hydropower, water storage and/or other purposes.

The deviation between natural and impacted flow pattern is derived by performing two model runs of the hydrological model (in this case LPJmL), resp. with and without the disturbance. The deviation is calculated from as the 'amended annual proportional flow deviation' (AAPFD; Ladson and White (1999) and implemented as described by (Biemans et al., 2011):

$$AAPFD = \left[ \sum_{i=1}^{12} \left( \frac{Q_i - Q_{i0}}{\bar{Q}_{i0}} \right)^2 \right]^{\frac{1}{2}} \quad (2)$$

This deviation is averaged over the years of record. In the formula,  $Q_i$  stands for the runoff in the  $i^{\text{th}}$  month,  $Q_{i0}$  for the natural runoff in the  $i^{\text{th}}$  month and  $\bar{Q}_{i0}$  for the year-averaged natural runoff. The natural runoff is taken from a run by the hydrological model where anthropogenic disturbances have been 'switched off', *i.e.* without river dams and with historical climate input (1900-1930). The value of AAPFD may range from 0 for undisturbed rivers to  $+\infty$ ; in general, values above 3 denote a strong deviation.

Data on existing river dams are taken from the GRanD database (Lehner et al., 2011); this database contains the ~7000 biggest dams in the world (out of an estimated 50,000). A projection of future dams was made by Fekete et al. (2010). Recently also other projections have been made, *e.g.* Zarfl et al. (2015).

The present model does not cover the (combined) effects of the smaller dams, which may have relatively little impact on water flow but still have a direct fragmenting effect.

### 3.5 Water temperature

Surface water temperature is calculated by the global hydrological model PCR-GLOBWB as described by Van Beek et al. (2012). This is a physically based model, coupling a surface water energy balance to the river discharge model. The results are given at a 30' grid base and match quite well with available temperature data on rivers and lakes in global datasets.

# 4 Biodiversity responses in rivers

## 4.1 Land-use or nutrients

The land-use effect on the relative biodiversity index (MSA) of rivers (water type 3) is calculated either from the fraction non-natural land-use (FRHLU) in the upstream catchment (the default option) or from the total phosphorus (TP) concentrations (as an alternative option). The equations are based on Weijters et al. (2009), slightly modified by Janse et al. (2015), in which further explanation and figures are given.

The default equation is:

$$MSA_{\text{Rivers.LU}} = 1 - 0.70 * FRHLU \quad (3)$$

with FRHLU = fraction non-natural land-use in the upstream catchment.

The function is based on 74 data points from 12 studies, mainly on fish and macro-invertebrates;  $R^2 = 0.33$ .

The alternative equation, based on phosphorus:

$$MSA_{\text{Rivers.P}} = \text{MAX}(0, 1 - 1.93 * [TP]) \quad (4)$$

in which [TP] is the total phosphorus concentration in  $\text{g P m}^{-3}$ .

This function is based on 20 data points from only 3 studies, again on macro-invertebrates and fish;  $R^2 = 0.40$ . It is roughly assumed that  $\text{PO}_4 = 0.5 * \text{TP}$ .

(Note: a significant relationship with nitrogen was not found in this study.)

## 4.2 Hydrological disturbance

The impact of hydrological disturbance (abbreviated as ‘\_HY’) on biodiversity intactness in rivers is described by: (Janse et al., 2015)

$$MSA_{\text{Rivers.HY}} = \text{MAX}(0.1, -0.3985 x + 0.60) \quad (5)$$

with  $x = {}^{10}\log(\text{AAPFD} + 0.1)$

The relationship is based on 23 data points from 20 studies, again mainly on fish and macro-invertebrates;  $R^2 = 0.10$ . The function was set up in such a way that it produces the value of 1 for  $\text{AAPFD} = 0$  (i.e. no disturbance). The function is cut-off at an (arbitrary) lower value of 0.1.

# 5 Biodiversity responses in wetlands

## 5.1 Land-use

For wetlands (GLWD types 4-12):

$$MSA_{\text{Wetlands.LU}} = 1 - 0.87 * FRHLU \quad (6)$$

with FRHLU = fraction human land-use in the catchment of the wetland.

The function is based on 265 data points from 24 (sub)studies, covering a variety of biotic groups: plants, mosses, fishes, amphibians, macro-invertebrates, birds, mammals;  $R^2 = 0.23$ . The data set mainly covered the wetland types 4, 5, 6 and 9; the categories 7 and 8 were underrepresented.

Recall that for the wetland types 4, 5 and 6, which are assumed to be connected to the river network, the catchment is taken as all upstream pixels; for the other types (7-12) their catchment is assumed to be confined to the 30' cell in which they are located.

Due to data limitations, it was not feasible to derive a relationship with nutrient emissions (which would potentially be a more sensitive indicator than human land-use).

*Converted* wetlands are assigned an MSA value of 0.1, equal to cropland in the terrestrial model GLOBIO 3.5 (PBL, 2016).

## 5.2 Hydrological disturbance

For floodplain marshes and swamps (water types 4 and 5):

$$MSA_{\text{Wetlands.HY}} = 0.3519 * \exp\left(\frac{0.5885}{x+1.5636}\right) \quad (7)$$

with  $x = {}^{10}\log(\text{AAPFD}+0.1)$

The function is based on 29 data points, from 19 studies, the majority covering plants but also animal groups were represented. The function is an asymptotic relation fitting the mean MSA values of 0.60 ( $\pm 0.21$ ), 0.53 ( $\pm 0.05$ ) and 0.46 ( $\pm 0.10$ ) for a low, medium and high flow disturbance (which were assigned a mean AAPFD of 0.3, 1 and 3, respectively) (Kuiper et al., 2014; Janse et al., 2015). (Note: as the original analysis was based on comparison of the effect sizes per disturbance group, the statistical power is given as standard errors rather than an  $R^2$  value; the values for medium and high disturbance were significant at the  $P < 0.0001$  level.)

For all other water types, no impact of hydrological changes is currently implemented (*i.e.*, the '\_HY' function equals 1.0).

# 6 Biodiversity responses in lakes

For lakes (water type 1), the biodiversity assessment is based on its trophic state, *i.e.* the average total nitrogen (TN) and total phosphorus (TP) concentrations in the incoming water.

The MSA is approximated by a sigmoid relationship with TP, derived from a logistic regression on the data set. A small value of 0.001 g P m<sup>-3</sup> is added to cope with possible zero values. The analysis was done for shallow (< 3m average depth) and deep lakes separately (Janse et al., 2015):

$$MSA_p = \frac{\exp(a + b * \log(TP + 0.001))}{1 + \exp(a + b * \log(TP + 0.001))} \quad (8)$$

in which TP is total phosphorus in g P m<sup>-3</sup> and 'log' means the natural logarithm (e<sup>log</sup>).

For deep lakes: a = -4.002, b = -1.176

For shallow (< 3m) lakes: a = -2.089, b = -1.048

The functions are based on 17 studies (11 on shallow and 6 on deep lakes) with 103 data points (some of which represented compiled data from many underlying studies); the standard error in the mid-range is around 0.08 MSA units for the shallow lakes and about 0.10-0.16 for the deep lakes. (Note: as the function is derived from a back-transformation of a logistic regression the fit cannot be expressed as an R<sup>2</sup>). The data points together cover algae, macrophytes, macro-invertebrates, fishes and zooplankton. The different regression coefficients for deep and shallow lakes reflect the natural differences between the two: shallow lakes are often naturally mesotrophic and dominated by macrophytes that may buffer extra nutrient additions to some extent, whereas deep lakes are naturally oligotrophic and are more vulnerable as they lack this buffer.

Ideally, in the model application, the natural trophic state of a lake (or *reference* TP concentration) should be subtracted from the concentration modelled by GNM. This could be done by taking the difference between a scenario run and a 'zero-scenario' run (= excluding all anthropogenic influences). This has not yet been implemented, but the error is probably limited as the natural phosphorus concentrations are mostly very low, apart from exceptional cases.

The number of studies on nitrogen, or phosphorus and nitrogen combined, were much more scarce, making it difficult to derive a sound relationship. Despite phosphorus mostly being the main limiting nutrient in freshwaters, there are indications of the additional importance of nitrogen for biodiversity in some instances, mostly in tropical waters but also in some temperate ones. Nitrogen can be considered as a subsidiary factor, still allowing a high biodiversity at high phosphorus conditions provided nitrogen is very low (James et al., 2005).

A separate, comparable logistic regression for TN is implemented in the model (with TN in g N m<sup>-3</sup>):

$$MSA_N = \frac{\exp(a + b * \log(TN + 0.01))}{1 + \exp(a + b * \log(TN + 0.01))} \quad (9)$$

For deep lakes: a = 0.145, b = - 4.768

For shallow lakes: a = 0.264, b = - 0.998

Finally, the relations for TP and TN are combined by selecting the highest value, analogous to (the complement of) the limiting nutrient concept for algal or plant growth; it means that characteristic species can survive if at least one of the nutrients is in low concentration.

$$MSA_{\text{Shallow.Nut}} = \text{MAX}(MSA_{\text{Shallow.P}}, MSA_{\text{Shallow.N}}) \quad (10)$$

$$MSA_{\text{Deep.Nut}} = \text{MAX}(MSA_{\text{Deep.P}}, MSA_{\text{Deep.N}}) \quad (11)$$

Hydrological impacts on lakes were not included in the current model.

## 7 Cyanobacteria in lakes

As an additional output, the model calculates the average biomass of cyanobacteria in lakes (g ww m<sup>-3</sup>) as a function of TP, TN and water temperature, using the empirical model by Håkanson et al. (2007), which is composed of a combination of several empirical relations; for the basic one (on TP) N=86 and r<sup>2</sup> = 0.76.

$$CB = 0.001 * [5.85 * \log_{10}\{1000 * \max(TP, 0.005)\} - 4.01]^4 * f_{\frac{TN}{TP}} * f_T \quad (12)$$

with

$$f_{\frac{TN}{TP}} = 1 \text{ IF } \frac{TN}{TP} > 15; \text{ ELSE } f_{\frac{TN}{TP}} = 1 - 3 * \left\{ \frac{TN}{TP * 15} - 1 \right\}$$

and

$$f_T = 0.86 + 0.63 * \left\{ \left( \frac{T}{15} \right)^{1.5} - 1 \right\} \text{ IF } T \geq 15; \text{ ELSE } f_T = 1 + 1 * \left\{ \left( \frac{T}{15} \right)^3 - 1 \right\}$$

where TP and TN in g m<sup>-3</sup>; CB = cyanobacteria (g ww m<sup>-3</sup>); f<sub>TN/TP</sub> = dependence on the TN/TP ratio; f<sub>T</sub> = temperature dependence; T = median surface water temperature in growing season (°C).

Please note that the in f<sub>T</sub> the left-hand function applies when T=15 °C (so f<sub>T</sub> = 0.86).

Following Håkanson and Boulion (2001), the growing season is defined as the period where epilimnetic water temperature exceeds 9 °C.

Water temperatures (for a given climate scenario) are calculated by PCR-GLOBWB, taken as monthly values.

The same function is applied to both shallow and deep lakes.

# 8 Aggregation

When applying the model for a certain scenario, the obtained results per pixel and per water type can be mapped directly to depict regional patterns. They can also be aggregated in several ways: over drivers, over water types and over regions, to obtain average  $MSA_{Aquatic}$  values.

## Aggregation over drivers, per water type

In case of multiple drivers affecting a certain water type, aggregation is performed by multiplication of the different factors, as it is assumed that the drivers are independent. In the current model this is applicable for rivers and floodplain wetlands. The equations are:

Lakes (water type 1):

$$MSA_{Lakes} = MSA_{Lakes.Nut} \quad (13)$$

This function is different for shallow and deep lakes (as described in section 3.2).

Rivers (water type 3):

$$MSA_{Rivers} = MSA_{Rivers.LU} * MSA_{Rivers.HY} \quad (14)$$

Floodplain wetlands (water types 4-5):

$$MSA_{Wetlands} = MSA_{Wetlands.LU} * MSA_{Wetlands.HY} \quad (15)$$

Other wetlands:

$$MSA_{Wetlands} = MSA_{Wetlands.LU} \quad (16)$$

## Aggregation of water types (per cell)

The average aquatic MSA per pixel is calculated as the area-weighted average of the values for the water types present. The aggregation is based on the *area* of water bodies (rather than for instance their volume), as the focus of the model is on the areas, analogous to the terrestrial model. Hence:

$$MSA_{Aqua}(Cell) = \frac{\sum Area_{watertype}(Cell) * MSA_{watertype}}{TotalWaterArea(Cell)} \quad (17)$$

## Aggregation over regions

Aggregation over regions is done by calculating the area-weighted averages for the relevant cells (*i.e.* the cells where water (of the respective type) is indeed present, according to the GLWD map). Two methods are implemented, based on the water area, or based on the number of surface water containing pixels; the areal method is used as the default option.

So, after multiplying the aquatic MSA value of a pixel by its water area, the values for all pixels in the region of interest are summed and then divided by the total water area in the region:

$$MSA_{Aqua}(Region) = \frac{\sum Area_{water} * MSA_{Aqua}}{WaterArea(Region)} \quad (18)$$

Regions of interest may include:

- IMAGE economic regions (24);
- OECD economic regions (15 or 3);
- Biomes;
- River catchments;
- Ocean catchments
- The whole world

This is also done *per main water type*, to calculate the average MSA for lakes, for rivers or for wetlands separately.

Details of these aggregations, including lists of derived variables, are given in the Appendix.

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# Appendix

This appendix gives some more details on the aggregation.

In the post-processing, the MSA results are also expressed as MSA-weighted area (km<sup>2</sup>). Table A1 gives a list of these aggregated variables. The total area per water type, as derived from the map, are also listed.

**Table A1. List of aggregated output variables**

AreaLakesSum	Sum of the lakes area (km <sup>2</sup> )
MSAAreaLakesSum	Sum of the MSA-weighted lakes area (km <sup>2</sup> )
AreaWetlandsLocalSum	Total area of isolated wetlands (water types 7-12) (km <sup>2</sup> )
AreaWetlandsNetworkSum	Total area of wetlands in the network (water types 4-6) (km <sup>2</sup> )
AreaWetlandsOrigSum	Total original GLWD wetlands area (km <sup>2</sup> )
AreaWetlandsConvertedSum	The area of wetlands converted to agriculture (km <sup>2</sup> ), scenario compared to GLWD original
MSAAreaWetlandsCorrectedSum	Sum of MSA-weighted wetlands area, corrected for the converted wetlands (MSA value of 0.1 given to the converted wetlands)
AreaRiverSum	Sum of the rivers area (km <sup>2</sup> )
MSAAreaRiverSum	Sum of the MSA-weighted area rivers (km <sup>2</sup> )
AquaticAreaRem	The remaining aquatic area (lakes + rivers + non-converted wetlands) (km <sup>2</sup> )
AquaticAreaOrigSum	The original aquatic area according to the GLWD map, including non-converted wetlands (km <sup>2</sup> )
MSAAreaAquaticSum	Total remaining MSA-corrected aquatic area (km <sup>2</sup> )

Moreover, a number of *derived outputs* are calculated, listed in table A2

Percentages of pixels resp. water area with MSA  $\geq$  0.8

Percentages of pixels resp. water area with MSA  $<$  0.8

Percentage of lakes with high cyanobacteria conc.

Percentage of lakes with low cyanobacteria conc.

**Table A2. List of derived output variables**

LowCyanoConc	# of cells with low cyanobacteria concentration
HighCyanoConc	# of cells with high cyanobacteria concentration
LowCyanoConcArea	Sum of lake area (km <sup>2</sup> ) with low cyanobacteria concentration
HighCyanoConcArea	Sum of lake area (km <sup>2</sup> ) with high cyanobacteria concentration
LakeHQ	# of cells with high ( $>0.8$ ) MSA value
LakeLQ	# of cells with low ( $<0.8$ ) MSA value

LakeHQArea	Sum of lake area (km2) with high (>0.8) MSA value
LakeLQArea	Sum of lake area (km2) with low (<0.8) MSA value
WetlandHQ	# of cells with high (>0.8) MSA value
WetlandLQ	# of cells with low (<0.8) MSA value
WetlandHQArea	Sum of wetland area (km2) with high (>0.8) MSA value
WetlandLQArea	Sum of wetland area (km2) with low (<0.8) MSA value
RiverHQ	# of cells with high (>0.8) MSA value
RiverLQ	# of cells with low (<0.8) MSA value
RiverHQArea	Sum of river area (km2) with high (>0.8) MSA value
RiverLQArea	Sum of river area (km2) with low (<0.8) MSA value

Finally, the *contribution* of the different drivers to the total MSA loss are calculated, by taking the difference between the situation with and without the particular driver. The calculation is done locally (per water type per pixel). In case of multiple drivers, the impact per driver  $i$  is calculated as:

$$Contrib_{driver(i)} = \frac{(1 - MSALoss_{driver(i)}) * (1 - MSALoss_{total})}{N_{drivers} - \sum_{i=1}^N MSALoss_{driver(i)}} \quad (A1)$$

That is, the impact of a certain driver on MSA is less than its 'nominal' value if the MSA was already reduced by another driver (as the impact of the different drivers are multiplied). The contributions are again area-weighted to calculate the overall impact of a driver for larger regions. These output variables are listed in table A3.

**Table A3. List of output variables denoting the contribution to MSA loss per driver.**

MSAALossWetLocLU	MSA-weighted area loss of isolated wetlands due to land use (km2)
MSAALossWetNetLU	MSA-weighted area loss of network wetlands due to land use (km2)
MSAALossWetNetHY	MSA-weighted area loss of network wetlands due to hydrology (km2)
MSAALossWetNetP	MSA-weighted area loss of network wetlands due to eutrophication (km2)
MSAALossWetLocP	MSA-weighted area loss of isolated wetlands due to eutrophication (km2)
MSAALossWetConv	MSA-weighted area loss due to wetland conversion (km2)
MSAALossRivLU	MSA-weighted area loss of rivers due to human land use (km2)
MSAALossRivHY	MSA-weighted area loss of rivers due to hydrological changes (km2)
MSAALossRivP	MSA-weighted area loss of rivers due to eutrophication (km2)
MSAALossLake	MSA-weighted area loss of lakes (km2)

The output variables from these tables have been used in assesment reports such as 'Rethinking' (PBL, 2010), OECD Environmental Outlook to 2050 (OECD, 2012) and GBO4 (PBL, 2014).