https://doi.org/10.5281/zenodo.8076281

Eutrophication potential of the stream network of the Danube Basin

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CITATION
Nagy E., Honti M., Istvánovics V., Gulbeyaz Ö., Karakaya N., Evrendilek F. (2023) Eutrophication potential of the stream network of the Danube Basin. In: Teubner K., Trichkova T., Cvijanović D., eds. *Tackling present and future environmental challenges of a European riverscape*. IAD Proceedings, 1:8076281.
DOI: 10.5281/zenodo.8076281

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Received: 18. April 2023
Accepted: 02. May 2023
Published: 23. June 2023

Abstract Eutrophication management is a more complicated task in running waters than in lakes and reservoirs, as network topology and longitudinal transport modulate system response to nutrient supply through dilution and short water residence time. The paradigm of lake eutrophication management is to force nutrient limitation of algal biomass by the reduction of nutrient loads. In streams, however, application of this paradigm was obviously unsuccessful in many cases, while it worked in others. Complex catchment modelling revealed that proliferation of phytoplankton in streams required the coincidence of three independent factors: adequately high nutrient supply, an inoculum of algae from the upstream environment, and a suitable downstream hydromorphology that provides sufficiently long time for algal growth. Standing water bodies in the stream network are not optimal habitats for fluvial algae and may disrupt phytoplankton development along the flow. At the same time, algae adapted to standing water conditions get washed out into the streams and may temporarily determine the trophic status of the downstream network. These phenomena suggest that eutrophication at the basin level is determined by the interaction of various factors, so its modelling requires a complex approach. The application of detailed, dynamic eutrophication models in large river basins needs immense amounts of data and computational power. To overcome this obstacle, we elaborated a novel, simplified steady-state network eutrophication model that targets to approximately quantify eutrophication potential of rivers in large basins. The model focuses only on the most important drivers of stream eutrophication and its data requirements can be covered from online databases. A case study is presented for the Danube Basin.

Keywords: network topology, phosphorus, light, meroplankton, scenario analysis

1 Introduction

Eutrophication is the enhanced growth of algae, periphyton, or macrophytes caused by excess plant nutrients (OECD, 1982). But what are the management implications of this definition? In standing water bodies, algae and nutrients spend the water residence time (typically several algal generation times) together in a mixed reactor (Figure 1). Accordingly, a strong positive correlation exists between mean phosphorus concentration and mean biomass in a wide range of phosphorus (Sas, 1989), which means that both variables are proper indicators of eutrophication.

In rivers, advection and network topology usually prevent a strong relationship between nutrients and phytoplankton biomass (Figure 2; Wehr and Descy, 1998; Istvánovics and Honti, 2012). Although nutrient concentrations have key importance with respect to eutrophication in the recipient standing waters and are often used as an index of eutrophication in rivers as well (Van Nieuwenhuyse and Jones, 1996; Dodds, 2006), they do not properly characterize river eutrophication. The proper measure of the latter is only algal biomass.

We aimed at capturing the time-averaged spatial eutrophication patterns in the Danube River network. For this purpose, the PhosFate-TAPIR time-averaged phytoplankton growth model developed for mesoscale catchments (Honti et al., 2010; Istvánovics et al., 2014) was further simplified for convenient use in large catchments. The simple, flexible, conceptual stream network eutrophication model has relatively low data requirement that can be satisfied from generally available databases – a particularly important feature when studying shared river basins. The model is suitable to analyze future scenarios.

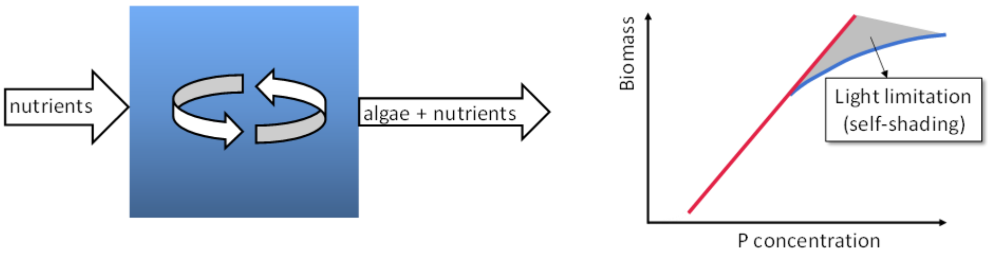

Figure 1: Scheme of algal growth in lakes and reservoirs (left); the relation of mean biomass to mean phosphorus (right).

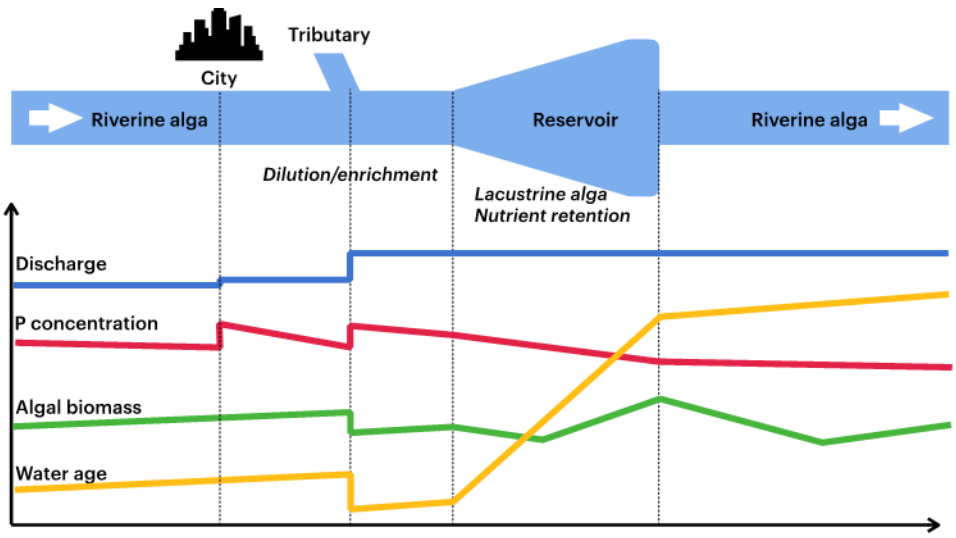

Figure 2: Discharge, phosphorus concentration, algal biomass as chlorophyll concentration, and water age profiles along a schematic river segment.

2 Material and methods

2.1 MODEL SETUP

Data sources are summarized in Table 1. The model consists of three modules (Figure 3). First, the mean annual runoff is estimated by feeding the adjusted empirical function of Berkaloff and Tixéront (1958) by potential evapotraspiration (PET) and annual precipitation maps. After accumulating runoff into discharge in every sub-catchment of the JRC CCM2 database (subcatchment areas vary from 0.01 to 177 km^2), travel time is estimated based on the river network topology and the location of lakes and reservoirs. The combination of topological, hydrological and hydraulic factors determines whether or not an increase in nutrient loading in a given watercourse will cause eutrophication. In other words, this module of the model estimates the susceptibility (vulnerability) of rivers to eutrophication.

Second, phosphorus load is calculated from land use and population data. Effective area-specific loads were assigned to 6 land use categories obtained by re-classifying the CORINE land use categories on the basis of mean values from previous Central-European applications of the PhosFate model (Kovács et al., 2008; Honti et al., 2010; Istvánovics et al., 2014). Daily per capita P emission was set to the usual 2 g P. The P removal efficiency of wastewater treatment plants (WWTPs) was assumed to be 90% in Germany, 70% in Austria, 0% in Moldova, Ukraine, and Serbia, and 30% elsewhere. No retention of P in watercourses was considered; retention in lakes and reservoirs was estimated using the OECD (1982) model.

The third module calculates algal growth. Two groups of algae are distinguished: lacustrine and river (meroplanktonic) algae. Their growth and mortality depend on habitat type, residence time, P concentration and light conditions. Habitats are identified as lakes if the water residence time in the JRC CCM2 elemental reaches of the stream network graph exceeds 1 day and as rivers if it is shorter. Both groups grow at a growth rate of 0.2 d-1 in their own habitat and decay at the same rate outside of it. We assume that one unit of P is required to produce one unit of chlorophyll (1µg P : 1µg Chl-a). When the available P supply is exhausted, growth stops completely. The meroplanktonic algae spend a fraction of their time settled on the bottom, so they travel slower downstream than the water. This means that the higher the proportion of time spent settled and floating, the higher the apparent growth rate of meroplankton compared to the 'real' growth rate of 0.2 d-1. This ratio is approximated by a method developed to estimate the distribution of fine sediment between the bottom and the water column (Honti at al., 2018). Light available to floating and settled algae is identical to the illumination at the middle and at the bottom of the water column, respectively. The light dependence of the growth rate is described by a hyperbolic tangent function.

The model was validated against long-term (roughly the past two decades) mean discharge and chlorophyll data.

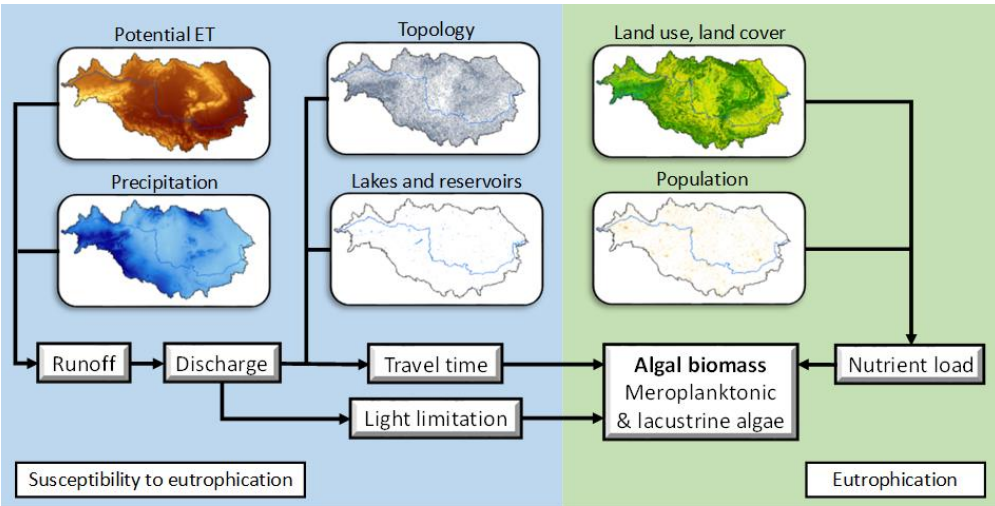

Figure 3: Structure of the simplified river network eutrophication model (Potential ET = PET)

Table 1: Data sources

TYPE OF DATA	DATABASE	SOURCE
River network	JRC CCM2	https://data.jrc.ec.europa.eu/dataset/fe1878e8-7541-4c66-8453-afdae7469221
Lakes, reservoirs	Open-Streetmap	https://www.openstreetmap.org/
Land use	CORINE 2018 & GLC	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 https://www.eea.europa.eu/data-and-maps/data/global-land-cover-2000-europe
Precipitation, potential evapotranspiration	WorldClim	https://worldclim.org/
Population	EUROSTAT	https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/grids
Population UA, MD	Wikipedia	
Discharge	GRDC	https://grdc.bafg.de
Concentration of chlorophyll *a*	TNMN	(https://www.icpdr.org/main/activities-projects/tnmn-transnational-monitoring-network

Table 2: Scenarios implemented in the model

Scenarios	Symbol	Description
Baseline		Observed mean data
Scenario 1		No wastewater treatment anywhere.
Scenario 2		90% phosphorus removal in all WWTPs.
Scenario 3		No human population, no urban and inert areas, no arable lands and pastures, no reservoirs.
Scenario 4		5% reduction in rainfall, 5% increase in PET, enlarging each reservoir by 20%, water abstraction to irrigate 30% of arable land to satisfy a plant demand equivalent to 700 mm/yr precipitation.
Scenario 5		No reservoirs.

2.2 SCENARIOS

In addition to the baseline scenario using observed data, five scenarios were investigated to understand how nutrient emission, reservoir construction and climate change influence eutrophication (Table 2). Scenarios 1 and 2 aimed at comparing the two extremes of point P management: the complete lack of sewage treatment and the implementation of the best wastewater treatment technology across the whole Danube Basin. Scenario 3 estimated the "pristine" trophic status by eliminating major human impacts, meaning the exclusion of arable land, human population, and reservoirs. Scenario 4 accounted for major impacts of climate change, that is reduced precipitation, increased PET, increased water retention in reservoirs and enhanced irrigation of arable land. Scenario 5 examined the impact of modification of network topology by eliminating water retention in reservoirs.

3 Results and discussion

3.1 THE BASELINE SCENARIO

For its simplicity, the model simulated well the average discharge at 306 points across the river network and reasonably reproduced the pattern of chlorophyll concentrations along the flow (Figure 4) consistently observed in the Danube (Dokulil, 2014). The model showed that algae started to grow immediately downstream of Vienna where the slope decreases, travel time increases, and nutrient availability is high. The biomass plateaued in between Budapest and the confluence of the Tisa River. The Drava, Tisa and Sava Rivers together double the discharge that dilutes the meroplankton travelling along the Danube. After these confluences, the channel of the Danube deepens, and the meroplankton can no longer regenerate because of light limitation. This process is further amplified in the Iron Gate Reservoirs. The systematic underestimation of chlorophyll downstream of the Iron Gate was due to the lack of accounting for channel heterogeneity. We estimated channel depth from discharge that implies a uniform cross-sectional depth. The estimated depth and associated light conditions did not support meroplankton growth along the lower Danube. In reality, however, Stoyneva (1994) showed the role of shallows in supporting meroplankton growth along the Bulgarian section of the Danube.

Of the largest tributaries, the Tisa River and the downstream section of the Sava, Velika Morava and Prut Rivers are eutrophic, while the Inn and the Drava Rivers had a favorable trophic status (Figure 5) in broad agreement with the pattern observed during the Joint Danube Surveys (Dokulil and Kaiblinger, 2014).

In line with our previous findings (Honti et al, 2010; Istvánovics et al., 2014), spatial distribution of phytoplankton biomass indicated that large and very large lowland rivers with long free-flowing sections and without large tributaries are the most susceptible to eutrophication. Both large tributaries and reservoirs may disrupt river continuity with respect to phytoplankton growth. The most conspicuous example of tributary-induced discontinuity was the collapse of phytoplankton downstream of the confluence of the Tisa and Sava Rivers within a short distance. A similarly conspicuous example is the confluence of the highly eutrophic Szamos River with the hitherto oligotrophic Tisa River that basically influences the trophic status of the whole downstream section of the main river (Honti et al., 2008; Istvánovics et al., 2010, 2011, 2014). Reservoirs force a change in community structure selecting for species avoiding high turbulence, often including cyanobacteria and dinoflagellates (Uherkovich, 1971).

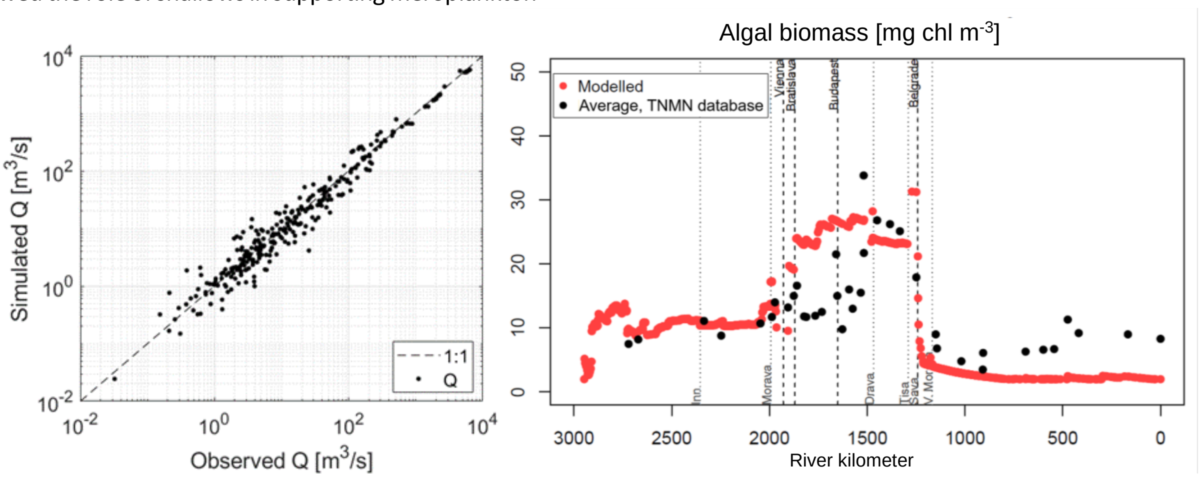

Figure 4: Comparison of measured and calculated discharge (Q, left) and algal biomass profile along the Danube (right).

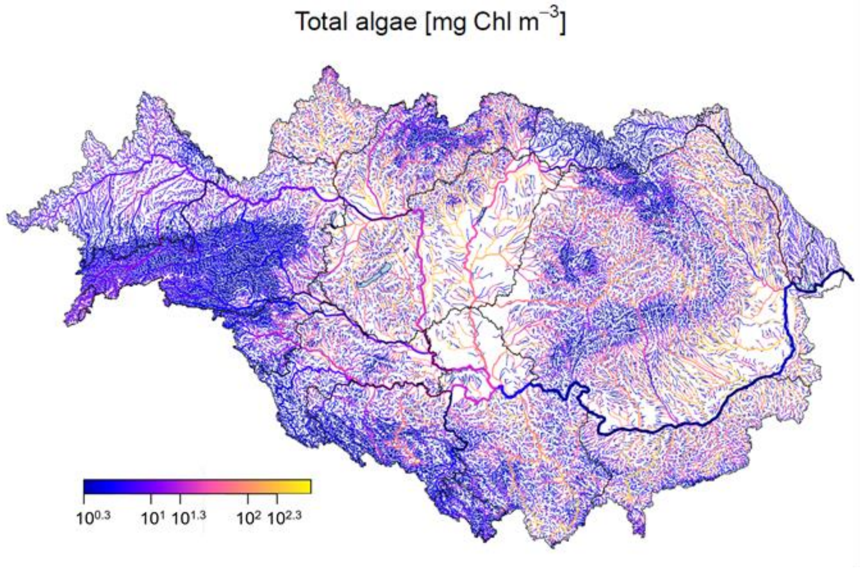

Figure 5: Distribution of simulated concentration of chlorophyll [mg m-3) in the Danube River network.

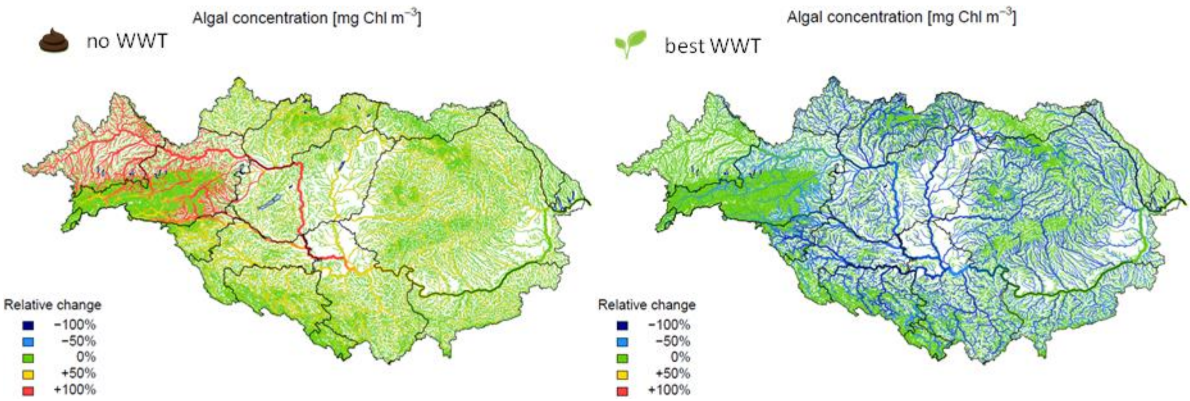

Figure 6: The relative change map of chlorophyll concentration compared to the baseline scenario when there is no sewage treatment (Scenario 1; left) and the best wastewater treatment technology is implemented (Scenario 2; right) across the whole Danube Basin.

3.2 SCENARIO ANALYSIS

Scenario 1 indicates that the efficient sewage treatment is a major factor that maintains the favorable present trophic status of the stream network in Germany and Austria (Figure 6). Without sewage treatment, streams turn eutrophic in the upper Danube catchment with the exception of the lowest order streams and mean biomass increases by a factor of 4 in the Danube (Figure 7). A significant trophic improvement could be achieved in the middle and lower Danube and in numerous large tributaries by introducing the best wastewater treatment technology across the whole Danube Basin (Scenario 2), stressing the importance of the wastewater management initiative of the ICPDR (2021).

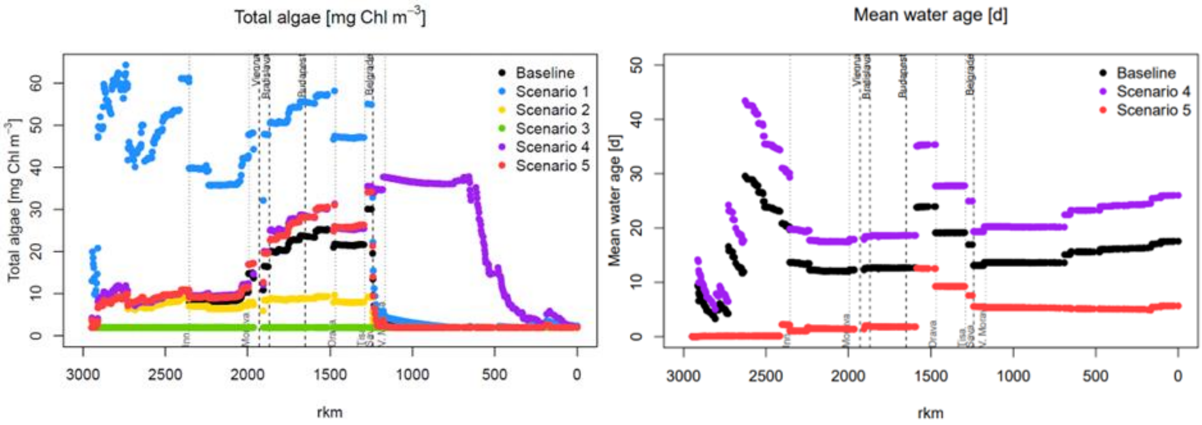

Figure 7: The algal biomass (left) and water age (right) profiles along the Danube in different scenarios, (Water age in Scenarios 1 and 2 is identical to that in baseline scenario; and in Scenario 5 it is identical to Scenario 3).

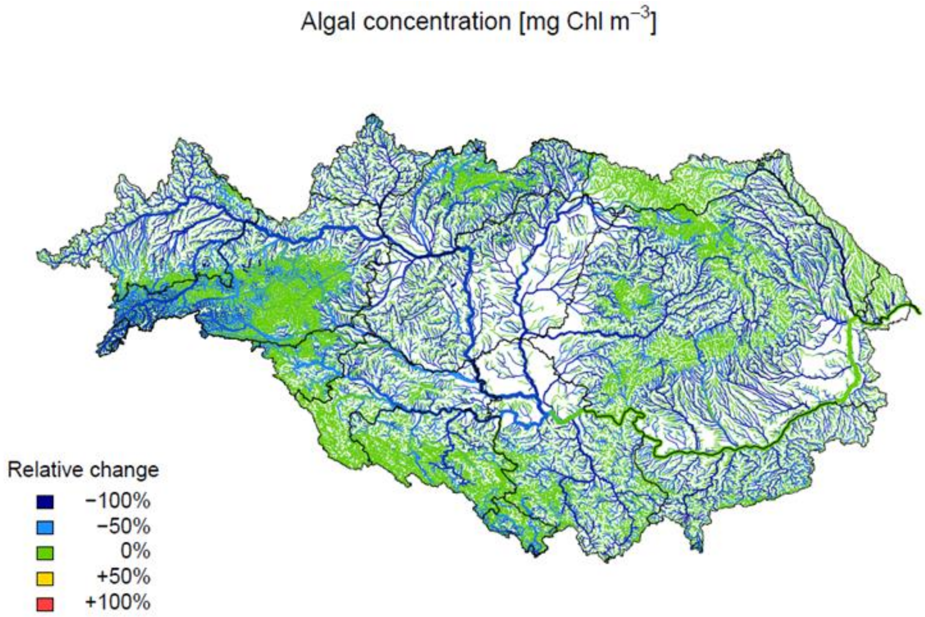

Figure 8: The relative change map of Scenario 3 (no major human impact) compared to Scenario 2 (best wastewater treatment technology).

Implementation of the best wastewater treatment technology across the whole Danube Basin (Scenario 2) would still result in about twice as high algal biomass in the upper and middle Danube than natural (Scenario 3; Figure 7). This is partly related to the higher water age in Scenario 2 compared to Scenario 3. A more detailed comparison of these two scenarios (Figure 8) suggests that present diffuse emissions are too high and should further be reduced. The primary target area where managing diffuse loads would have the largest impact on the trophic state of the stream network is the catchment of the Inn River.

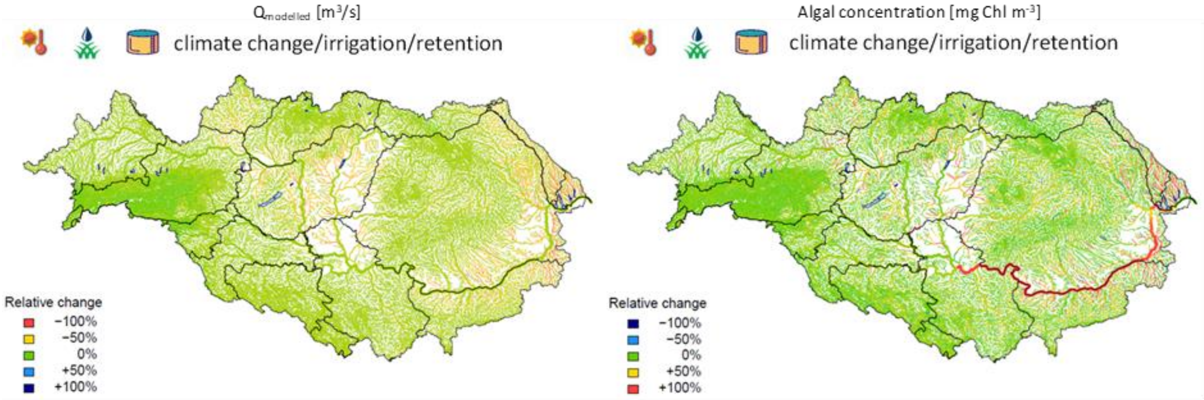

Figure 9: The relative change map of discharge (left) and chlorophyll concentration (right) under the impact of climate change Scenario 4) compared to the baseline scenario.

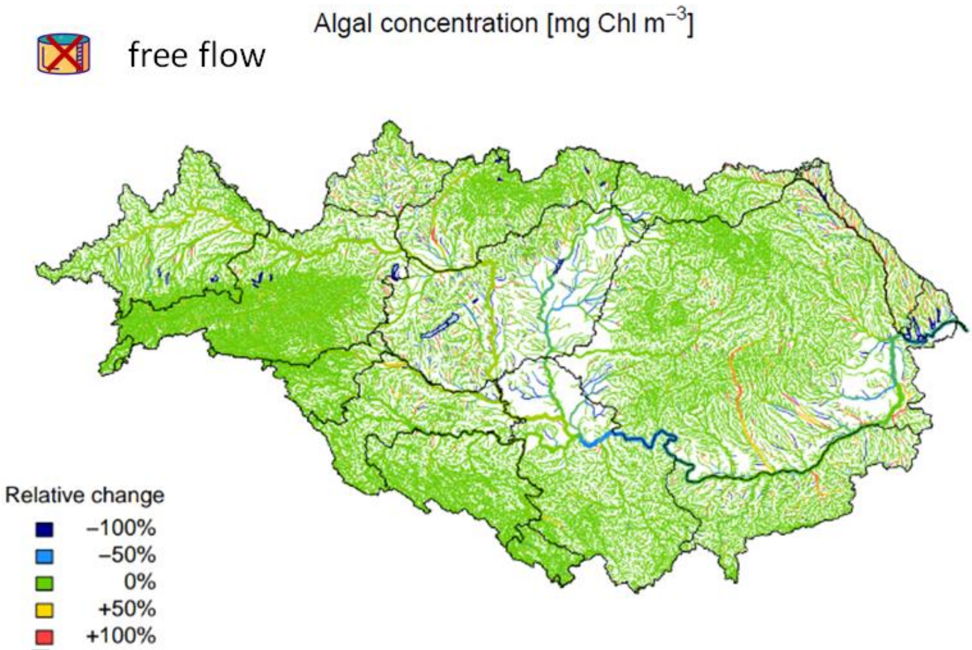

Figure 10: The relative change map of chlorophyll concentration in Scenario 5 (no reservoirs) compared to the baseline scenario.

The climate change scenario (Scenario 4) caused a general decrease in modelled discharge (Figure 9). This led to shallower channel depth and improved light climate. Simultaneously, a considerable increase in water age occurred along the Danube River (Figure 7). Cumulation of the upstream changes was particularly pronounced along the lower Danube, where phytoplankton biomass increased by a factor of up to 4 (Figures 7 and 9).

The removal of reservoirs (Scenario 5) halves the water age along the Danube (Fig. 7) and decreases it in small streams of the river network even by orders of magnitude. Additionally, the absence of reservoirs restores the continuity of watercourses with respect to meroplanktonic growth. The combined effect of these two factors can lead to both a reduction and an increase in algal biomass in the river section downstream the removed reservoir, depending on local conditions (Figure 10). If the reservoir was eutrophic, the biomass will decrease along the section where lacustrine algae washed out from the reservoir have decayed. Conversely, we see an increase if the trophic level of the reservoir was not very high, and the dominant effect of its removal is a significant lengthening of the shallow, free-flowing section of the river, which is the ideal habitat for meroplanktonic algae. While removal of reservoirs has pronounced local effects on the downstream stretches of streams, the network-scale impact is small. Thus, along the Danube River a slight biomass increase is seen only in the middle section (Figure 7).

4 Conclusions

In general, the proposed very simple model was capable of capturing the present and potential eutrophication features of the Danube at the basin scale. The model clearly reflected the key importance of network topology and the meroplanktonic life history adaptation of fluvial algae in river eutrophication. A major benefit of holistic, basin-scale modelling was that response to management alternatives could be analyzed at a similar level. Responses to management alternatives often occurred several 100 kilometers downstream of the site of the intervention and conversely, strong local responses may not imply a significant network-scale response to management. The model provides flexibility by i) making possible to replace simplified assumptions with detailed and/or realistic input data and projections (e.g., data on wastewater treatment, spatially distributed climate change projections, etc.) and ii) being applicable from river basin to continental scales.

Acknowledgment This work was financially supported by the grant (NNE 129990) of the National Research, Development and Innovation Office (Hungary).

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