Ecological Indicators 18 (2012) 42–49

Contents lists available at SciVerse ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers

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ARTICLE INFO

Article history:
Received 21 February 2011
Received in revised form 14 October 2011
Accepted 19 October 2011

Keywords:
Coastal eutrophication
Water quality
Water pollution level
River natural concentration
Nitrogen
Phosphorus

ABSTRACT

The grey water footprint (GWF) is an indicator of aquatic pollution. We calculate past and future trends in GWFs related to anthropogenic nitrogen (N) and phosphorus (P) inputs into major rivers around the world. GWFs were calculated from past, current and future nutrient loads in river basins using the Global *NEWS* model. We present water pollution levels (WPLs), deduced from GWFs for more than 1000 rivers. The calculated GWFs and WPLs of the different river basins show a large variation among different periods. WPL values generally increased between 1970 and 2000. For the year 2000 about two-thirds of the basins have WPL values exceeding 1 for N or P, indicating that the pollution assimilation capacity has been fully consumed. Even though the other rivers have a WPL < 1, this does not guarantee that at sub-basin level or within particular periods of the year no eutrophication exists. High WPLs are generally found in rivers in tropical–subtropical areas. For dissolved organic N and P, the problems are located mostly in the southern hemisphere. The results indicate that many rivers may become more polluted with dissolved N and P in the future.

1. Introduction

Rapid increases in world population, food production and energy consumption over the past decades have changed land use and global hydrological cycles (Hoekstra, 2008). In many regions water scarcity and water pollution became an issue (Falkenmark, 1990; Arnell, 1999; Bouwer, 2000), including the mobilization of bioavailable nutrients, such as nitrogen (N) and phosphorus (P) in watersheds (Seitzinger et al., 2005). Significant fractions of this mobilized N and P enter surface waters and are transported by rivers to coastal seas (Seitzinger et al., 2005; Galloway et al., 2004). Human activities have thus altered global N and P cycles, resulting in eutrophication of lakes, rivers and coastal zones worldwide (Carpenter et al., 1998). Eutrophication has become a serious threat to water quality (Selman et al., 2008), reducing the biodiversity and ability of aquatic ecosystems to provide valuable ecosystem services for the world's population. Two of the most commonly recognized symptoms of eutrophication are harmful algal blooms and hypoxia.

Due to human activities, bioavailable N has nearly doubled and bioavailable P tripled in the environment (Howarth and Ramakrishna, 2005). Agriculture, sewage, urban runoff, industrial wastewater and fossil fuel combustion are the most common anthropogenic sources of nutrients delivered to freshwater systems which end up in coastal systems. The nutrient loading of many rivers has been increasing (Seitzinger et al., 2009; Kroeze et al., 2010). The sources of nutrients differ considerably among river basins. The growth of hypoxic zones in Europe and North America is attributed to fertilizer use in agriculture in particular (Seitzinger et al., 2010). Sewage and industrial wastewater are other important sources, as is atmospheric N deposition from fuel combustion and industries (Metcalf and Eddy, 2003). In South America, Asia and Africa, animal manure and sewage are often an important anthropogenic cause of eutrophication (Van Der Struijk and Kroeze, 2010; Yasin et al., 2010).

The water footprint is an indicator of freshwater use that considers the indirect as well as the direct water use of a consumer or producer (Hoekstra, 2008). The term 'grey water footprint' (GWF) to indicate the degree of freshwater pollution was introduced first by Hoekstra and Chapagain (2008). The GWF is defined as the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et al., 2011). Recent studies quantifying grey water footprints (e.g. Van Oel et al. (2009), Dabrowski et al. (2009), Gerbens-Leenes et al. (2009), Aldaya and Hoekstra (2010), Bulsink et al. (2010) and Mekonnen

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doi:10.1016/j.ecolind.2011.10.005

and Hoekstra (2010, 2011) focus on nitrogen pollution in a particular and on one region, or on particular activities or products.

We aim to analyze past, current and future trends in water pollution by nitrogen and phosphorus for major rivers around the world. To this end, we calculate the GWF following Hoekstra et al. (2011), using nutrient (N and P) loads in rivers according to the Global *NEWS* model. In addition, we test the sensitivity of this GWF to major assumptions (C_{nat} and C_{max}).

2. Materials and methods

We calculate GWFs based on N and P in world rivers calculated using the Global *NEWS* (Global Nutrient Export from WaterSheds) model. Future trends are based on the Millennium Ecosystem Assessment (MA) scenarios (Bouwman et al., 2009; Van Drecht et al., 2009; Seitzinger et al., 2010).

2.1. Grey water footprints

Hoekstra et al. (2011) define GWF as the pollutant load divided by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration C_{max}, in mass/volume) and its natural concentration in the receiving water body (C_{nat}, in mass/volume) (Eq. (1)).

$$\mathrm{GWF} = \frac{L_{add}}{C_{max} - C_{nat}} \quad (1)$$

where GWF = grey water footprint (km^3/year), L_{add} = additional (non-natural) nutrient load (Gg/year), C_{max} = maximum acceptable concentration (mg/l), and C_{nat} = natural concentration (mg/l).

$$L_{add} = L - C_{nat} \times Q_{act} \quad (2)$$

where L_{add} = additional (non-natural) nutrient load (Gg/year), L = total nutrient load (Gg/year) measured at river mouth, C_{nat} = natural concentration (mg/l), and Q_{act} = actual basin discharge (km^3/year).

The natural concentration C_{nat} is the concentration in the water body that would occur if there were no human influence. It is not zero, because all rivers naturally transport some nutrients. The GWF is an indicator of appropriated assimilation capacity. This capacity depends on the difference between the maximum allowable and the natural concentration of a substance. Therefore, the natural concentration is used in the calculation and not the actual concentration (Hoekstra et al., 2011). We calculate C_{nat} for major river basins (including endorheic basins) with population densities lower than 1 inhabitant per 10 km^2 as follows

$$C_{nat} = \frac{L}{Q_{act}} \quad (3)$$

where L = the total nutrient load (Gg/year) measured at the river mouth. For low population density basins we assume that L is close to the natural nutrient load.

Q_{act} = the actual basin discharge (km^3/year). In the Global *NEWS* model, Q_{act} reflects the amount of water discharged at the river mouth from the entire watershed.

The actual basin discharge (Q_{act}) and the basin population density (*PopDen*) are taken from the Global *NEWS* model inputs, while the nutrient load at the river mouth (L) is the model output. GWF is calculated for 1090 major endorheic river basins worldwide (i.e. rivers draining to the coast).

Using Eq. (3), we calculate C_{nat} for the year 1970 for about 300 watersheds. Next, we compare the average C_{nat} values for different years and scenarios with averages from the literature (Meybeck, 1982) (Table 1). Based on this comparison, we selected C_{nat} values to use in the GWF calculations for each pollutant. These C_{nat} values do not change over time or with scenarios.

The maximum acceptable concentration C_{max} can be interpreted as the maximum allowable concentration, based on literature values. To monitor the quality of fresh waters, various countries have set ambient water quality objectives for different substances. The objectives for N and P compounds found in the literature are typically annual, summer or winter averages. In this study, no seasonal dynamics are taken into account. The target concentrations that we take can be seen as an upper limit or a maximum acceptable value. Within Europe there is a large range of target values for different nitrogen and phosphorus compounds (Laane et al., 2005) and the worldwide range is even larger.

Our assumptions about C_{nat} and C_{max} are not basin-specific and account only to a limited extent for the variety in structure, geology, ecology, water quantity, land use and socioeconomic characteristics of river basins. Given the limited number of empirical studies and basin-specific datasets, we consider this appropriate for the purpose of our study. Moreover, using the same maximum allowable concentrations allows a fair comparison across rivers, which would be more difficult if different local standards – partly set on political grounds – were used.

GWFs for major world rivers are calculated from Global *NEWS* model outputs (nutrient load) and assumptions about natural and maximum acceptable pollutant concentrations. The effect of the total GWF in a river basin depends on the discharge available to assimilate the pollutant in the catchments (Hoekstra et al., 2011). This effect is quantified by calculating the water pollution level (WPL) per river basin, which indicates the degree of pollution of a water flow. The WPL in a river basin measures the fraction of the pollution assimilation capacity consumed and corresponds to the quotient of the GWF to the discharge (Hoekstra et al., 2011) (Eq. (4)).

$$\mathrm{WPL} = \frac{\mathrm{GWF}}{Q_{act}} \quad (4)$$

where WPL = water pollution level, GWF = grey water footprint (km^3), and Q_{act} = actual basin discharge (km^3/year).

A WPL of 1 means that the pollution assimilation capacity has been fully consumed. A WPL larger than 1 indicates serious pollution in the water body. WPL values lower than 1 indicate that there is an average enough river water to dilute the pollutant to below the maximum acceptable level at the basin scale. However, it does not guarantee that there are no local or periodic pollution problems within the basin.

2.2. Global NEWS model

The Global *NEWS* model calculates river exports of different forms of N and P as a function of human activities, basin characteristics and hydrology (Seitzinger et al., 2010). In the model, basins are defined on a 0.5° × 0.5° (longitude/latitude) as in the Water Balance Model (STN-30p, version 6.01) (Fekete et al., 2010). The model was implemented for past (1970), present (2000), and future years (2030 and 2050). Here, we focus on about 1000 of the largest rivers, as Global *NEWS* analyses indicate that this model is most reliable for river basins exceeding four grid cells.

The Global *NEWS* model inputs include information on basin characteristics and human activities in the basins. The outputs are nutrient export rates by river and the sources of these nutrients. This output is generated for nine forms of N, P and C: dissolved inorganic N and P (DIN and DIP), dissolved organic N, P and C (DON, DOP and DOC), total suspended solids (TSS) (Johannessen et al., 2005), and particulate forms of N, P, and C (PN, PP and POC) (Beusen et al., 2005; Harrison et al., 2005a, 2005b; Dumont et al., 2005). Details on Global *NEWS* are described by Mayorga et al. (2010) and Seitzinger et al. (2005)

Table 1
Summary of natural (C_{nat}) and maximum (C_{max}) concentrations used in GWF calculation compared with the values from the literature.

	C_{nat} calculated from the Global *NEWS* model (Eq. (3)) (mg/l)	C_{nat} values from the literature (Meybeck, 1982) (mg/l)	C_{nat} used here (mg/l)	C_{max} (mg/l)	European target level (Laane, 2005) (mg N/l)
DIN	0.2 (0.20–0.23)	0.12	0.2	1	2.59
DON	0.3 (0.30–0.30)	0.26	0.3	0.65	–
PN	1 (0.92–1.1)	–	1	1.5	–
TN	1.5 (1.4–1.5)	–	1.5	3.1	0.8–5
DIP	0.005 (0.0049–0.005)	0.01	0.005	0.12	0.01–1.86
DOP	0.016 (0.016–0.016)	–	0.016	0.03	–
PP	0.5 (0.44–0.52)	0.53	0.5	0.8	–
TP	0.52 (0.44–0.64)	0.55	0.52	0.95	0.048–0.9

The Global *NEWS* model has been thoroughly calibrated and validated (Beusen et al., 2005; Dumont et al., 2005; Harrison et al., 2005a, 2005b; Mayorga et al., 2010; Seitzinger, 2010; Van Der Struijk and Kroeze, 2010; Yasin et al., 2010). In general, 60–90% of the observed variation in nutrient yields of rivers worldwide can be explained by the latest versions of the Global *NEWS* model (Mayorga et al., 2010).

The future analyses are interpretations of the four MA scenarios (Alcamo et al., 2006). The MA scenarios are: global orchestration (GO) and order from strength (OS), which assume reactive environmental management, while technogarden (TG) and adapting mosaic (AM) assume proactive environmental management. GO and TG reflect trends towards globalization, while OS and AM point to regionalization. Several of the Global *NEWS* model inputs are anthropogenic drivers directly taken from the MA (Mayorga et al., 2010; Seitzinger et al., 2010). For model inputs not available from the MA, additional data sets were developed by interpreting the original MA assumptions (Bouwman et al., 2009; Van Drecht et al., 2009; Fekete et al., 2010). These include net surface N and P balances for river basins, based on N and P inputs and outputs. The N and P in sewage are estimated based on per capita incomes, use of detergents and human N and P emissions (Van Drecht et al., 2009). Future changes in hydrology follow the MA projections (Fekete et al., 2010).

The Global *NEWS* model output includes nutrient yield (Eq. 5) and load (Eq. (6)) at the mouth of rivers (Mayorga et al., 2010). Nutrient *load* is the annual total mass of nutrients (C, N or P) exported at the mouth of the river. Nutrient *yield* is the export of each nutrient species at the river mouth in kg/km^2 of watershed/year.

$$\text{Yield} = f \times (\text{RS}_{\text{pnt}} \times \text{RS}_{\text{dif}}) \quad (5)$$

where Yield = nutrient yield (kg/km^2/year), f = fraction (0–1) of elements from point and diffuse sources at river mouth, RS_{pnt} = export of pollutant from the watershed to streams from point sources (sewage), and RS_{dif} = export of pollutant from watersheds to streams from diffuse sources, natural and anthropogenic.

Nutrient loads (kg/year) are calculated from yields and basin area.

$$L = \text{Yield} \times A \quad (6)$$

where L = nutrient load (kg/year), Yield = nutrient yield (kg/km^2/year), and A = basin area (km^2). For other model equations and parameters see Seitzinger et al. (2010) and Mayorga et al. (2010).

3. Results

3.1. Natural concentration and maximum acceptable concentration

Using Eq. (3), we calculated the natural concentration (C_{nat}) of each nutrient for specific years and scenarios (Table 1). Our C_{nat} calculation results are generally in agreement with Meybeck (1982) (Table 1), who reviewed available empirical studies and estimated world averages of natural nutrient levels in rivers. Only for DIN, the calculated C_{nat} (0.2 mg/l) is higher than the published value (0.116 mg/l). PN, TN and DOP concentrations are not considered by Meybeck (1982). However, he determined total dissolved P (TDP; 0.025 mg/l) and DIP (0.01 mg/l), which implies DOP concentrations of approximately 0.015 mg/l (while our calculated DOP C_{nat} is 0.016 mg/l) (Meybeck, 1982). Therefore, PN can be assumed to be 1.06 mg/l, whereas the calculated PN is 1 mg/l. Thus the calculated natural concentrations are generally in agreement with the literature. Based on this, we selected values for C_{nat} to be used in the GWP calculations (Table 1).

The maximum allowable concentrations (C_{max}) are based on scattered information on target levels for N and P concentrations from the literature (Table 1). These levels vary among rivers, countries and continents. For instance, Laane (2005) concluded that within Europe different objectives exist for N and P compounds (Table 1). Worldwide, this range is probably even larger. Applying country-specific or watershed-specific values for C_{max} is not possible based on existing literature. We, therefore, defined C_{max} nutrient specific, but not varying among basins, over time or among scenarios. The C_{max} values used in GWF calculations are based on national surface water quality standards (Table 1). Basically, the assumptions are the middle of the range and for most nutrients they are about twice the C_{nat} value (Table 1). C_{max} of TN and TP are the sum of DIN, DON, PN and DIP, DOP, PP, respectively.

3.2. Water pollution levels for N and P for rivers in 1970, 2000, 2030 and 2050

We present spatially explicit past and future trends in WPL for different N and P species. We focus especially on DIN and DIP because these forms are readily biologically available. For future trends, this section focuses more on the GO scenario than on the others, because this can be considered a worst case for the environment in many world regions. Other scenarios are discussed in the supporting material.

3.2.1. Dissolved inorganic nitrogen (DIN)

We first present results for dissolved inorganic N (DIN) (Fig. 1). Between 1970 and 2000, the number of polluted rivers by DIN (WPL > 1) has increased by one-third worldwide. For the year 2000, we calculate the highest WPL values for Europe, Asia and North America. In total, 257 basins have a WPL > 1 for DIN in the year 2000 (Table 2). This is about 25% of the total number of basins in our analysis.

In all future scenarios, the number of rivers with WPL > 1 is increasing, but at different rates (Fig. 1, and supporting material). Between 2000 and 2050, the number of rivers with WPL > 1 increases by 11% (scenario AM) to 38% (scenario GO). The GO scenario has the largest number of nutrient polluted rivers in 2050 and the AM scenario the lowest. The relatively large increase in

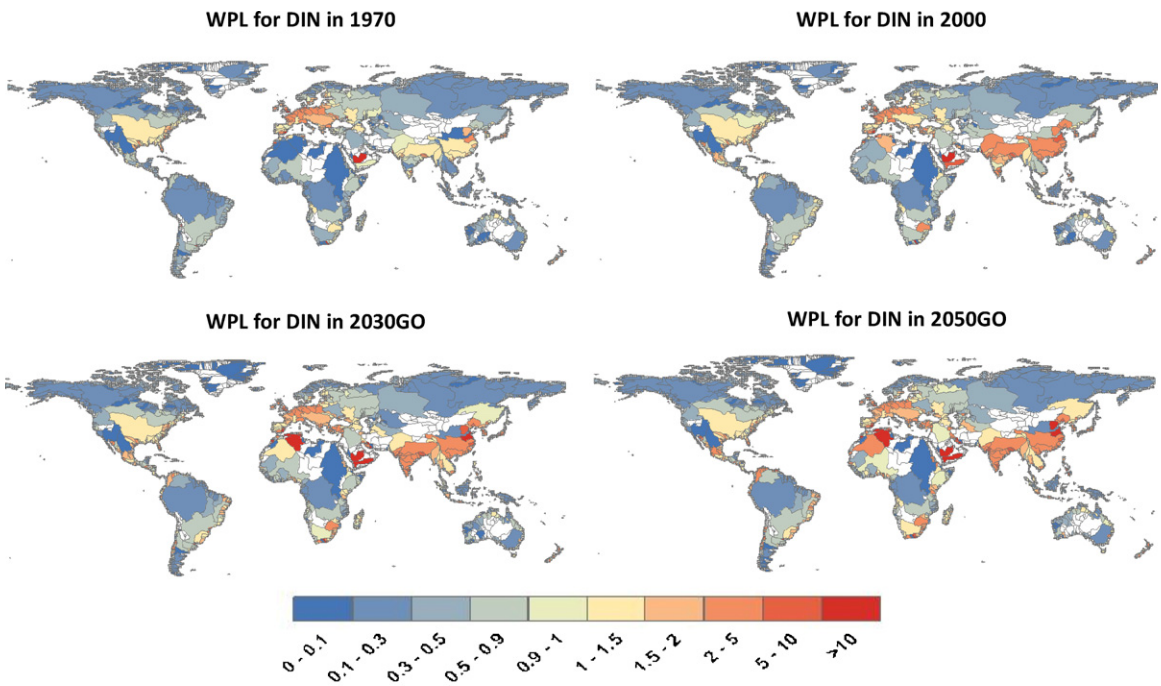

Fig. 1. Water pollution levels (WPLs) of major rivers for DIN in 1970, 2000, 2030 GO and 2050 GO.

the GO scenario is consistent with increased fertilizer use, manure excretion and per capita meat consumption in this scenario. The second largest number of polluted rivers is calculated for scenario OS, in line with the high population growth, low levels of fertilizer efficiency and poor wastewater treatment in OS. The increased fertilizer use efficiency and N removal from wastewater with low population growth of TG may explain the relatively low increase in watersheds with WPL > 1. The lowest increase for scenario AM can be explained by the integration of animal manure and recycling of human N from households coupled with a medium level of productivity and population growth assumed in this scenario.

It is interesting to note that regional patterns of pollution change over time. In 1970, DIN was mainly a problem in European rivers; while in 2000 it also became a problem outside Europe (Fig. 1). For example, in 1970 (Fig. 1) the situation in Southwest Europe was more serious than in America, South China and India. However, since 1970, DIN pollution in South China and India has become worse, whereas for Europe small improvements are calculated. Future WPL levels are high in Europe and Asia. It should be noted that some basins with very high WPL values on the Arabian Peninsula, Algeria and Southern Africa are rivers with very low discharge.

3.2.2. *Dissolved inorganic phosphorus (DIP)*

Next, we analyze results for dissolved inorganic P (DIP) (Fig. 2). In the year 2000, 117 basins have a WPL > 1 for DIP in the year 2000, which is about 10% of the total number of rivers analyzed here (Table 2). Increases in global river WPLs for DIP are projected for the past and all future scenarios. The trends for DIP are similar to that of DIN: a 25% increase in the number of rivers with WPL > 1 between 1970 and 2000 compared to 33% for DIN in the same period, and a 77% increase for DIP between 2000 and 2050 in the GO scenario (38% for DIN in the same time period). These global average increases are the net effect of regional increases in DIN and DIP river export (e.g. in Asia) and decreases (e.g. in Europe).

We present spatial patterns in WPL for 1970, 2000 and the GO scenario (Fig. 2). All scenarios (see supporting material) project an increase in WPL levels for major watersheds. The increase in WPL for DIP in the GO scenario can be explained by increased DIP inputs to rivers from phosphate detergents in sewage, fertilizers and manure. On the continent scale, WPL for DIP in South Asia, Africa and South America generally increase between 1970 and 2050 GO whereas the situation in North America, Europe and Oceania remains constant (Fig. 2). Remarkably, the WPL in Europe shows

Table 2
Three cases in the sensitivity analysis of WPL[a] for the year 2000. The cases differ in assumptions on C_{nat} and C_{max}. Cases are based on (M): Meybeck (1982), (A): own assumptions, (L): Laane (2005), and (N): calculated from the Global *NEWS* model.

			DIN	DON	PN	DIP	DOP	PP
Case 1	C_{nat}	Default	0.2	0.3	1	0.005	0.016	0.5
	C_{max}	Default	1	0.65	1.5	0.12	0.03	0.8
	# of basins WPL > 1		257	217	337	117	216	207
Case 2	C_{nat}	Lower	0.12 (M)	0.26 (M)	0.92 (N)	0.004 (N)	0.008 (A)	0.44 (N)
	C_{max}	Lower	0.5 (A)	0.45 (A)	1.2 (A)	0.01 (L)	0.015 (A)	0.6 (A)
	# of basins WPL>1		423	962	680	885	969	523
	% increase		65	343	102	656	349	153
Case 3	C_{nat}	Higher	0.23 (N)	0.30 (N)	1.08 (N)	0.01 (M)	0.016 (N)	0.53 (N)
	C_{max}	Higher	2.59 (L)	1.3 (A)	3 (A)	1.86 (L)	0.06 (A)	1.6 (A)
	# of basins WPL>1		49	29	64	24	18	64
	% decrease		81	87	81	79	92	69

[a] Water pollution level (WPL) = grey water footprint (GWF)/actual river basin discharge (Q_{act}).

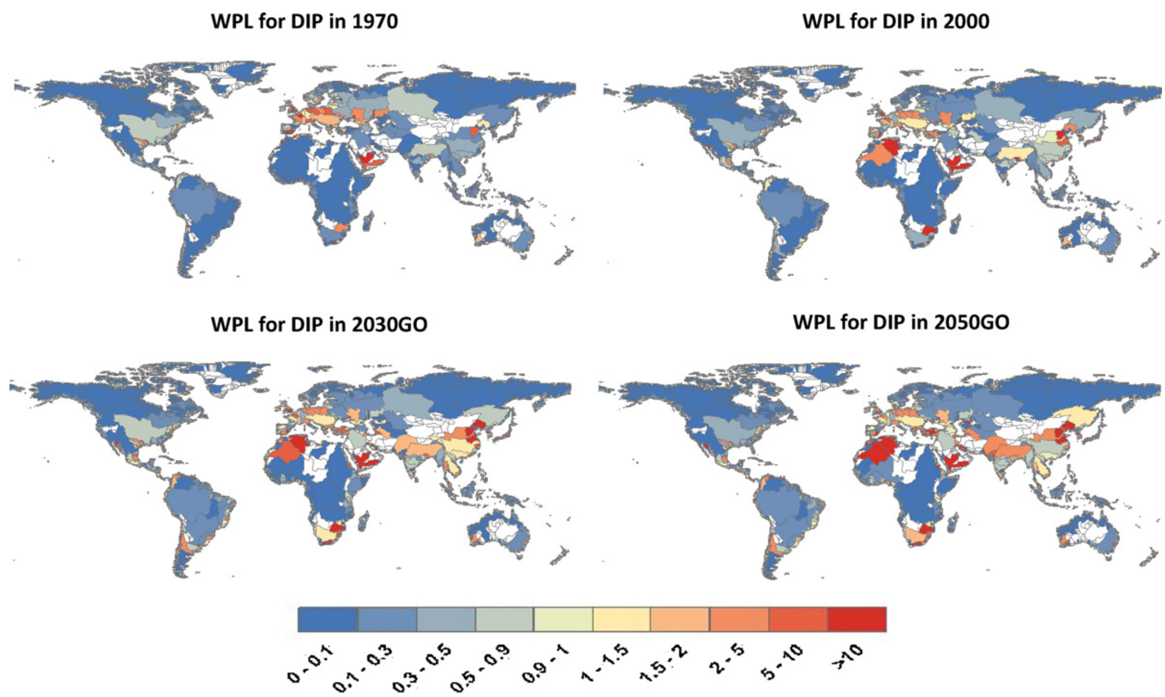

Fig. 2. Water pollution levels (WPLs) of major rivers for DIP in 1970, 2000, 2030 GO and 2050 GO.

a continuous decrease between 1970 and 2050 for the GO scenario. This is the result of environmental and agricultural policies. Largest changes in WPL for DIP are calculated for South Asia (Fig. 2).

3.2.3. Trends in overall WPL (2000–2050)

We present overall WPLs for N and P and identify the critical substances (Figs. 3 and 4, Table 3). For example, the overall WPL of N for the Rhine is 2.54 and the critical substance is DIN, which means the WPL for DIN (2.54) is higher than for DON or PN.

About two-thirds of the basins have overall WPL values exceeding 1 for N or P, and this water pollution may increase in the future. The percentage of river basins with an overall WPL > 1 for N in 1970 and 2000 is 66%, increasing slightly to 68% in 2050 GO. For P, these percentages are 30% for 1970, 33% for 2000 and almost 40% for 2050 GO. In addition, the absolute levels of WPL increase in the future: in 1970 20% of the rivers have a WPL exceeding 2, while in 2050 GO this is 30%.

We present results for 2000 for fifteen major rivers (Table 3), including the overall WPL and GWF for N and P, and their critical substance (results for other rivers are available in on-line material). For example, the overall GWF of the Amazon indicates that every year 4733 km^3 of water is needed to dilute N to maximum acceptable levels, which is less than the actual discharge (WPL < 1), and DON is the critical substance. The overall WPLs of N for most other rivers are exceeding 1, whereas the overall WPLs of P for nearly half of the rivers is larger than 1. DIN appears to be critical for river basins with considerable agriculture, such as the Mississippi, Chang Jiang, Indus, Zhu Jiang and Rhine.

The spatial variation in GWFs is large. High WPL basins are generally found in tropical–subtropical areas in all scenarios and years. However, for dissolved organic forms a difference between the Southern and the Northern hemisphere was clear. The Ganges, Yangtze and Amazon are river basins with the highest GWFs both for DIN and DIP. Likewise, their WPLs have generally increased between 1970 and 2000 and will continue to increase in future years, except for particulate N and P. However, WPLs vary largely among nutrient forms. In 2000, the percentage of rivers with a WPL exceeding 1 ranges between 11% (for N) and 54% (for P). In future years, this range is similar.

Low WPLs are calculated for one or more nutrient forms for a considerable number of river basins, including basins with a low population density such as the Amazon (Table 3), but also basins with a high population density. A WPL < 1 indicates that there is no pollution problem at the basin scale. As mentioned above, this does not mean that there is no risk for local pollution within basins. It should be noted that we calculate basin-wide averages for WPL.

3.3. Sensitivity analysis

We test the sensitivity of the calculated WPL values for changes in two uncertain parameters: C_{nat} and C_{max}. Three cases were defined (Table 2): a default case (Case 1) and a lower case (Case 2) and a higher case (Case 3) assuming lower and higher values of C_{nat} and C_{max}. Cases 2 and 3 differ only moderate from Case 1.

For Case 2, the number of rivers with WPL > 1 is 65–656% of the number in Case 1, depending on nutrient forms (Table 2). For Case 3 this is 69–92% (Table 2). These results indicate that the calculated WPL values are relatively sensitive to the assumptions on natural and maximum concentrations (Table 2).

4. Discussion

It is difficult to validate GWFs and WPLs, since the grey water footprint of a river basin cannot be measured directly. Therefore, GWF and WPL are calculated here from the well-validated Global *NEWS* model. Model calibration and validation has been essential during the development of Global *NEWS*. The Global *NEWS* model performs well on the global and continental scale. Moreover, the natural nutrient concentrations in rivers that we calculate from the Global *NEWS* model results are in line with Meybeck (1982). The GWF and WPL values calculated from the Global *NEWS* model are relatively sensitive to the assumed natural concentration (C_{nat})

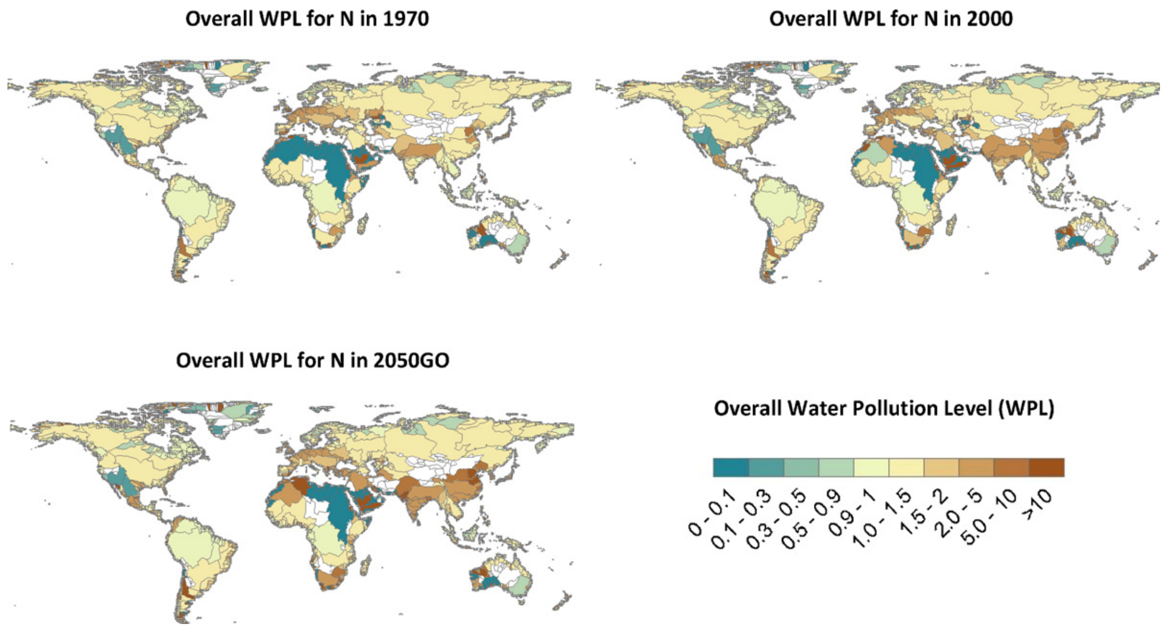

Fig. 3. Overall water pollution levels (WPLs) of major world rivers in the years 1970, 2000 and for 2050 for the global orchestration (GO) scenario for nitrogen.

and maximum concentration (C_{max}). Relatively moderate changes in these concentration levels (10–50%) resulted in a large difference in WPL (up to a factor of 6.5). This indicates that the assumptions on C_{nat} and C_{max} largely influence the results of our analysis.

We did not explicitly consider the direct visible effects of coastal eutrophication, such as harmful algal and vegetation blooms. The most serious threat from eutrophication is probably the decrease in dissolved oxygen levels in bottom water, when phytoplankton dies. This affects the provision services such as fish and shellfish for local communities, commercial fisheries, tourism and recreation. In addition, it is a threat to biodiversity. Animal manure and commercial fertilizers from agriculture are generally the primary contributors to eutrophication. Sewage and industrial wastewater treated before discharge is the second most important source. In South America, Asia and Africa, sewage and industrial wastewater is often untreated and therefore an important cause of coastal eutrophication.

Several issues need further investigation. First, natural and maximum acceptable concentrations are not easily determined. More experimental and modeling studies are needed to improve our estimates of natural and maximum acceptable concentrations for basins in different conditions, for example climate zones, sizes, basin productivities, water quantities. Second, we performed a limited sensitivity analysis. In would be interesting to also test the sensitivity of the results to other assumptions underlying the Global *NEWS* model, or GWF and WPL calculations.

This study is a first exploration of how the Global *NEWS* model can be used to calculate grey water footprints for nitrogen and phosphorus at the global scale. The results can be used to identify regions where rivers are most polluted. In combination with other

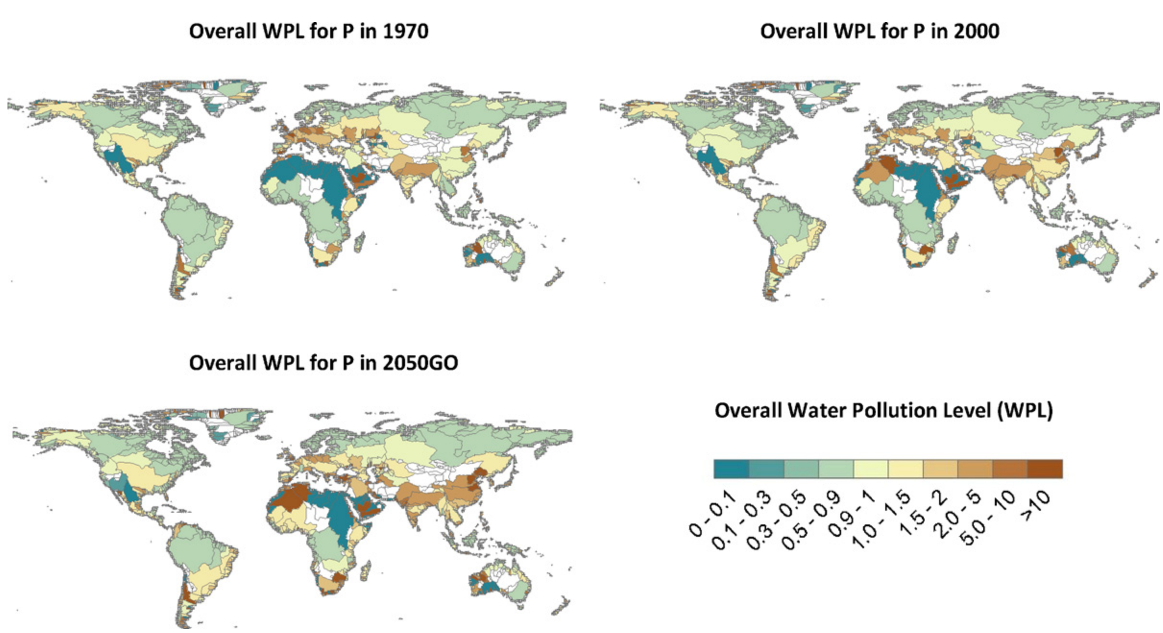

Fig. 4. Overall water pollution levels (WPLs) of major world rivers in the years 1970, 2000 and for 2050 for the global orchestration (GO) scenario for phosphorus.

Table 3
Calculated overall GWF and WPL of fifteen major rivers in different continents for N and P in 2000.

	Discharge (Q_{act}) (km^3/year)	N			P		
		Overall GWF[a] (km^3/year)	Overall WPL[a]	Critical substance	Overall GWF (km^3/year)	Overall WPL	Critical substance
Amazon	5026	4733	0.94	DON	4038	0.80	DOP
Congo	1783	1723	0.97	DON	1459	0.82	DOP
Mississippi	538	719	1.34	DIN	537	1.00	DOP
Ob	290	340	1.17	DON	269	0.93	DOP
Yenisei	423	440	1.04	DON	368	0.87	DOP
Niger	369	383	1.04	DON	330	0.89	DOP
Chang Jiang	437	1089	2.49	DIN	519	1.19	DOP
Ganges	703	2665	3.79	PN	2653	3.77	PP
Volga	234	311	1.33	DON	218	0.93	DOP
Zambezi	389	391	1.01	DON	331	0.85	DOP
Indus	38	96	2.51	DIN	78	2.04	DOP
Mekong	400	417	1.04	PN	379	0.95	PP
Zhujiang	142	358	2.52	DIN	159	1.12	DOP
Rhine	58	149	2.54	DIN	62	1.06	DOP

[a] The Overall GWF (or WPL) is the largest calculated grey water footprint (or water pollution level) among all different nutrient forms of N or P.

Global *NEWS* model outputs, we can identify the likely causes of this pollution and how these may change in the future.

5. Conclusion

We show that grey water footprints calculated from Global *NEWS* results are useful indicators for water pollution. Validation and calibration of global pollution studies is essential, and it is important to realize that indicators such as GWF and WPL cannot be validated themselves, but that they are derived from validated model results.

The GWFs and WPLs vary largely among rivers, scenarios and years. We calculate that currently about two-thirds of the rivers have an overall WPL > 1 for N or P, indicating serious pollution problems. There are large regional differences. South Asia and Europe are regions with high WPL levels for almost all scenarios and years. For DIN, this should be interpreted as serious river water pollution typically caused by manure and fertilizer inputs. For DIP, likely reasons are sewage discharge and detergents containing phosphates.

For about one-third of the world's rivers we calculate relatively low WPLs. However, a WPL < 1 is no guarantee that at the sub-basin level no eutrophication exists, because we do not account for spatial variation within the basin. When we calculate a WPL > 1, on the other hand, this is a strong indication for serious pollution.

From 1970 to 2000 the percentage of rivers with WPLs > 1 has been increasing for all nutrient forms of N and P by 0.5% (PN) to 6% (DIN). In 2000 the highest percentage of rivers with WPLs > 1 is for DON (54%) followed by PN (30%), PP and DIN (18%), DOP (17%) and DIP (9%).

For the future we calculate increasing pollution levels, but not for all forms of N and P. The percentage of rivers with a WPL > 1 increases by 5–9% for dissolved N and P between 2000 and 2050 (Scenario GO). For particulate N and P, the percentage of rivers with WPL > 1 decreases by 1–2.6%, respectively, between 2000 and 2050. These trends are the net effect of trends in human activities on land, and changes in hydrology associated with climate change, irrigation, damming and consumptive water use. At the continental scale, the temporal trends range from large increases to large decreases in WPL levels. For example, the WPL for N for Asia doubles between 2000 and 2050 in the GO scenario, while there are several Asian watersheds for which WPL is projected to decrease.

The pollution problem is projected to shift from industrialized countries to developing countries in the coming decades. This is the case for all nutrient forms and scenarios. The largest changes in WPLs were found in South East Asia. This can be explained by the fast population growth in South East Asia and by the lack of wastewater treatment plants and technologies.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolind.2011.10.005.

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