



Research article

Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic pathways

P.J.T.M. van Puijenbroek^{a,*}, A.H.W. Beusen^{a,b}, A.F. Bouwman^{a,b}^a PBL Netherlands Environmental Assessment Agency, PO Box 30314, 2500 GH The Hague, the Netherlands^b Department of Earth Sciences, Geochemistry, Faculty of Geosciences, Utrecht University, PO Box 80021, 3508 TA Utrecht, the Netherlands

ARTICLE INFO

Keywords:

Nutrients

Nitrogen

Phosphorus

Waste water

Sewage

Shared socioeconomic pathways

ABSTRACT

This paper presents global estimates of nutrient discharge from households to surface water based on the relationships between income and human emissions represented by protein consumption, degree of connection to sewerage systems, presence of wastewater treatment plants and their level of nutrient removal efficiency. These relationships were used to construct scenarios for discharge of nutrients with waste water based on the five Shared Socio-economic Pathways for the period from 1970 to 2050. The number of inhabitants connected to a sewerage system will increase by 2–4 billion people between 2010 and 2050. Despite the enhanced nutrient removal by wastewater treatment, which will increase by 10%–40% between 2010 and 2050, nutrient discharge to surface water will increase in all scenarios by 10%–70% (from 10.4 Tg nitrogen (N) in 2010 to 13.5–17.9 Tg N by 2050 and from 1.5 Tg phosphorus (P) in 2010 to 1.6–2.4 Tg P by 2050). In most developing countries, nutrient discharge to surface water will strongly increase over the next decades, and in developed countries it will stabilize or decrease slightly. A global decrease in nutrient discharge is possible only when wastewater treatment plants are extended with at least tertiary treatment in developing countries and with advanced treatment in the developed countries. In future urban areas that will be developed over the 2010–2050 period, options for recycling can be included in wastewater management systems. A separate collection system for urine can yield 15 Tg N yr⁻¹ and 1.2 Tg P yr⁻¹, which can be made available for recycling in agriculture. The SDG 6.3 about safely treated waste water by 2030 will be reached in the developed countries in 2030. In the developing countries, the goal will be reached by 2050 only under SSP1, SSP2 and SSP5.

1. Introduction

Eutrophication accounts for the foremost aquatic ecosystem management problem in rivers, lakes, and estuaries around the world (EEA, 2012; OECD, 2012; Janse et al., 2015). Eutrophication is caused by nitrogen (N) and phosphorus (P) nutrient loading of surface water and leads to higher primary production in rivers and lakes (Butcher, 1947). Ecosystem services, such as drinking water supply, fisheries, aquaculture and tourism, can be negatively affected by eutrophication (Diaz and Rosenberg, 2008; Zhang et al., 2010). Impacts are not restricted to fresh water, since coastal seas are also affected by eutrophication, ultimately leading to harmful algal blooms and hypoxia due to the decay of algal biomass (Diaz and Rosenberg, 2008; Kemp et al., 2009; Gilbert et al., 2010).

The two most important sources of nutrients in freshwater systems are nutrient losses from agriculture and wastewater discharge from households and industry (Bouwman et al., 2005). In many countries,

households are the main point sources of nutrients in densely populated urban areas and the environmental pressure they cause is determined by the level of sanitation, connection to sewerage systems or lack thereof, and presence and level of wastewater treatment. Sanitation improvement is strongly determined by national health and environmental policy (EEC, 1991; WHO and Unicef, 2017b).

The aim of this paper is to project the future pressures from nutrient discharge from point sources based on scenarios, as well as the potential for collecting nutrients from human excretion for recycling in agriculture. We use the Global Nutrient Model (GNM) (Beusen et al., 2016), which is part of the Integrated Model to Assess the Global Environment (IMAGE) (Stehfest et al., 2014). GNM includes both diffuse sources (agriculture, natural ecosystems) and point sources. The GNM point source model is an update of the model presented by Van Drecht et al. (2009) and Morée et al. (2013) with updates of (i) the historical data on connection to sewerage systems and wastewater treatment up to the base year 2010, (ii) relationships between per-capita incomes and

* Corresponding author.

E-mail address: peter.vanpujenbroek@pbl.is (P.J.T.M. van Puijenbroek).<https://doi.org/10.1016/j.jenvman.2018.10.048>

Received 14 June 2018; Received in revised form 4 October 2018; Accepted 14 October 2018

Available online 25 October 2018

0301-4797/ © 2018 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Table 1
Total and urban population, GDP and description of the five SSPs.

Property	SSP1	SSP2	SSP3	SSP4	SSP5
Keyword	Sustainability	Middle of the road	Fragmentation	Inequality	Conventional development
Total population in 2050 (10 ⁶ inhabitants and % relative to 2010)	8477 (+23%)	9181 (+33)	9963 (+45)	9213 (+33)	8629 (+24)
Urban population in 2050 (10 ⁶ inhabitants and % of population)	6549 (77)	6154 (67)	5445 (55)	6952 (76)	6654 (78)
GDP/capita in 2050 (1000 US\$ and % increase related to 2010)	34 (+243)	25 (+156)	18 (+83)	24 (+146)	43 (+330)
Technological development	Rapid	Medium	Slow	Slow	Rapid
Progress towards development goals	Good	Some	Failure to achieve goals	Highly unequal	Market-driven
Inequality	Less	Medium	High	High	Less
Attitude towards environmental problems	Proactive	Indifferent	Reactive	Reactive	Reactive

protein consumption, detergent use, connection to sewerage systems, wastewater treatment and nutrient removal efficiency; these relationships are used in future scenario projections for these aspects.

We selected the five Shared Socio-economic Pathways (SSPs), the most recent family of scenarios developed for the Intergovernmental Panel on Climate Change (Kriegler et al., 2014; O'Neill et al., 2014; Van Vuuren et al., 2014) (Table 1). SSP1 is a scenario in which major efforts are made to achieve sustainable development while reducing both resource intensity and the use of fossil fuels. SSP2 is a business-as-usual scenario, and SSP3 represents a fragmented world with regions differing widely in economic development. SSP4 is a world with large inequalities. Finally, SSP5 involves traditional development with a focus on economic growth and new technology with a continued dependence on fossil fuels. These scenarios have already been implemented in IMAGE (Van Vuuren et al., 2017b) to assess the impact of population growth and economic development on food and energy production, land-use change and climate change (Van Vuuren et al., 2017a) and fertilizer use and diffuse nutrient loads from agricultural land (Beusen et al., 2016; Mogollón et al., 2018).

Improved sanitation, or hygienic separation of human excreta from human contact (Unicef and WHO, 2015) constitutes a major goal to improve global health as defined in the Sustainable Development Goal (SDG) 6.2, which reads: 'by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations' (UN, 2015). If improved sanitation would be realized through the construction of sewerage systems that directly discharge into surface water (i.e. lacking wastewater treatment) or with only primary treatment, this may result in an increase in nutrient loading (Ligtvoet et al., 2014). Hence, a scenario of population growth and policy strategies aimed at achieving SDG 6.2 can result in an increase in nutrient loading, particularly if not combined with SDG 6.3, which reads: 'by 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated waste water and substantially increasing recycling and safe reuse globally' (UN, 2015). We will therefore assess the outcomes of the SSPs, in terms of how the environment progresses towards SDG 6.3.

The collection of human excreta from urban areas for use in agriculture was common up to the early 20th century, most substantially in Europe, Asia, and North America (Morée et al., 2013). With the increasing number of households with access to sewerage systems, this recycling of human excretion became less common over the course of the 20th century, and nowadays is only practiced in developing countries. In the future, recycling of nutrients for agricultural use will have to become more important, especially since global phosphorus reserves are being depleted (Van Vuuren et al., 2010; Cordell et al., 2011; Mihelcic et al., 2011). Various options for gathering human excretion are available, such as separate collection of human urine from households or public toilets, as 80% of total human N excretion and 62% of total human P excretion are in urine (Mihelcic et al., 2011; Roy, 2017; Simha and Ganesapillai, 2017). Struvite can be produced from urine separately or in combination with feces and household waste, which

can be used as NP fertilizer (Cordell et al., 2011; Wielemaker et al., 2018). For the rural population, there are small-scale solutions to use P as fertilizer, sometimes in combination with biogas production (Cordell et al., 2011).

2. Material and methods

2.1. Global Nutrient Model

The IMAGE-GNM point source model is discussed in detail in Van Drecht et al. (2009) and Morée et al. (2013). Here, we first present a brief outline, and in the following sections we discuss the updates of both the model and input data. Concerning the household emissions of nutrients, the model uses human food consumption as the main source of N and P in household waste water, N and P emissions from industry, and P emissions from the use of detergents (Fig. 1). Human nutrient intake is based on food protein intake, which is corrected for retail and household waste and for protein stored in hair, nails and skin, etc. The total of urine and feces excretion is assumed to equal intake minus losses. P emissions from detergent depend on the use of laundry and dishwasher detergents and the content of P in the detergent.

The fate of household waste water depends on the presence or absence of a sewerage system (Fig. 1). Part of the waste water from inhabitants not connected to a sewerage system may be recycled in agriculture, or it ends up in the 'other' pool, together with leakage from sewerage systems, retail and household waste. The effluent of sewerage systems can be treated by wastewater treatment plants or directly be discharged to surface water. Without a sewerage system, excreta is collected either in septic tanks or pit latrines, or there is open defecation. The level of nutrient removal depends on the type of wastewater treatment.

Future total discharge of nutrients to surface water is affected by socio-economic drivers quantified in the SSP scenarios (Fig. 1): (i) the total volume of household emissions is directly proportional to the population size; (ii) income affects protein consumption through the human diet, as well as the use of laundry and dishwasher detergents; (iii) the construction of sewerage systems and wastewater treatment plants is a response to health and environmental problems. This is a long-term investment and is related to the per-capita income in each country or region. In addition, the attitude towards health and environmental problems, available technology and equality are aspects that we use in the scenario storylines for the urgency and willingness to construct sewers and wastewater treatment plants.

2.2. Model update

Data on total, urban and rural population and per-capita incomes are available on all countries, for the period from 1970 to 2010 and 2010 to 2050, for the SSPs (Jiang and O'Neill 2017; KC and Lutz, 2017) (Table 1, SI. 2). Income is expressed in Gross Domestic Product (GDP) per capita, measured in purchasing power parity (PPP) and expressed in US dollars (2005 exchange rate) (Leimbach et al., 2017). For protein consumption, sewerage system connection (SC), nutrient removal (NR)

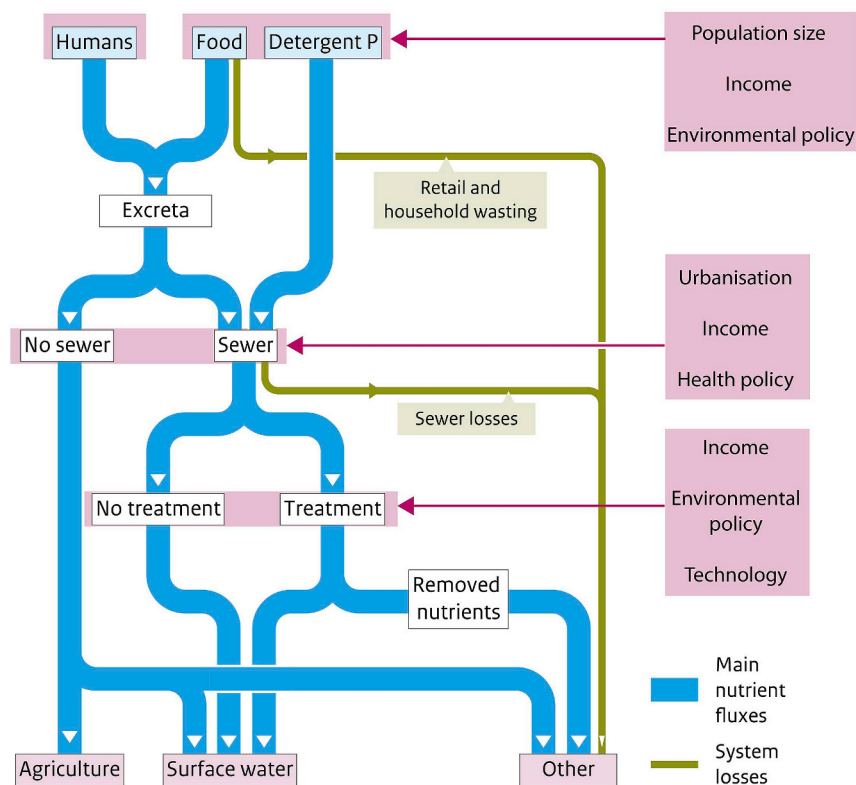


Fig. 1. Scheme of the wastewater nutrient flows in the IMAGE Global Nutrient Model (GNM). In the model, income is a driver of per capita protein consumption and of use of detergents; P content of detergents depends on environmental regulations; total fluxes are determined by population size. Sewerage connection and wastewater treatment are also related to income and can reduce nutrient discharge to surface water. Health and environmental policy and available technology are implemented in the scenarios in a qualitative way. Scheme is modified from Morée et al. (2013).

by wastewater treatment plants, and detergent use, we regressed historical data aggregated to the scale of world regions against per-capita GDP. The resulting regression equations were used to construct future regional trends based on GDP scenarios for the SSPs, from the year 2011 onwards. These regional trend lines were matched to the base year data for individual countries within each region using country-specific correction factors. The regression equations for protein consumption, SC and NR are shown in Fig. 2 a, b, c. For each regression equation five regression models (linear, exponential, logarithmic, polynomial and power) were compared using the correlation coefficient R^2 , the root mean square error and mean absolute error (Janssen and Heuberger, 1995), to select the model with the best fit (S.I. 5).

Protein consumption is based on FAO data (2017). Protein consumption can be related to income (Grigg, 1995; Bijl et al., 2017) and for countries without data on protein consumption and for the future protein consumption in scenarios, we used this correlation using data on IMAGE regions (see S.I. 1) for the years 1990, 2000 and 2010 (Fig. 2a). The selected regression equation was similar to Billen et al. (2013).

Data for SC are based on the previous model version (Van Drecht et al., 2009; Morée et al., 2013) and updated with information retrieved from the Joint Monitoring Program (JMP) and OECD (WHO and Unicef, 2015). The JMP database includes country-scale SC data based on national studies, but for most countries were only a few years available. Therefore, annual data for periods of 10 years were averaged to obtain decade information. In case of disagreement between JMP and OECD, OECD was selected. The data set thus obtained provides information on 200 countries, whereby 30 countries are based on OECD data, 142 countries on JMP data and 28 were either extrapolated to the year 2010 using past trends or corrected in the case of discontinuities (see S.I. 6).

Country-scale data on wastewater treatment on a global scale were available from Van Drecht et al. (2009), Reder (2017), OECD (2016) and UN (2017) according to the following scheme: OECD data were used for all countries with available data; for missing countries, data from Van Drecht et al. (2009) were used and compared with those collected by Reder and corrected if necessary (2017) (S.I. 6). The UN

data include total treatment without distinguishing treatment types and were used to compare with the sum of the treatment types calculated from the other data sources; in case of a difference, all treatment types were corrected to match with UN total treatment. For China, NDRC data were used (NDRC, 2016).

We distinguish primary, secondary and tertiary treatment with corresponding nutrient removal fractions (Table 2). The percentage removal by tertiary wastewater treatment was according to current levels of nutrient removal in Germany (EEA, 2014). For the scenarios, we also used the quaternary treatment type with N and P removal fractions of 0.95 (Table 2). For scenario projections, removal fractions of nitrogen (NR^N) and phosphorus (NR^P) are combined to the overall Nutrient Removal fraction (NR^{NP}):

$$NR^{NP} = f_{prim} * NR_{prim}^{NP} + f_{secon} * NR_{secon}^{NP} + f_{tert} * NR_{tert}^{NP} + f_{quart} * NR_{quart}^{NP} \quad (1)$$

Where f_{prim} , f_{secon} , f_{tert} and f_{quart} are fractions of total population with access to primary, secondary, tertiary or quaternary wastewater treatment installations, respectively.

Regarding laundry and dishwasher detergents, we updated the equations with per-capita GDP, as used by Van Drecht et al. (2009) and Van Puijenbroek et al. (Submitted). We assumed a P concentration of 0.0625 g P/g detergent for laundry detergents and 0.0006 g P/g detergent for P-free detergents; for dishwasher detergents we used 0.177 and 0.01 g P/g detergent for standard and P-free detergents (Van Drecht et al., 2009), according to recent European Union regulations (EC, 2011; EU, 2012).

Nutrient emissions from households lacking SC are an important flux, since, for example, most of the 40 investigated African cities with more than a million inhabitants lacked a functioning sewerage system (Miller and Parker, 2013). In cities lacking sewerage systems, part of the waste is recycled in agriculture, and the remainder is drained via ditches or canals (Miller and Parker, 2013; World Bank, 2016; SFD, 2017). In many sub-Saharan African cities, up to 60% of human waste is discharged largely uncontrolled during heavy rainfall (Nyenje et al., 2010). We assumed that N in the waste water from urban households that lack sewerage system connection is reduced by 20% due to

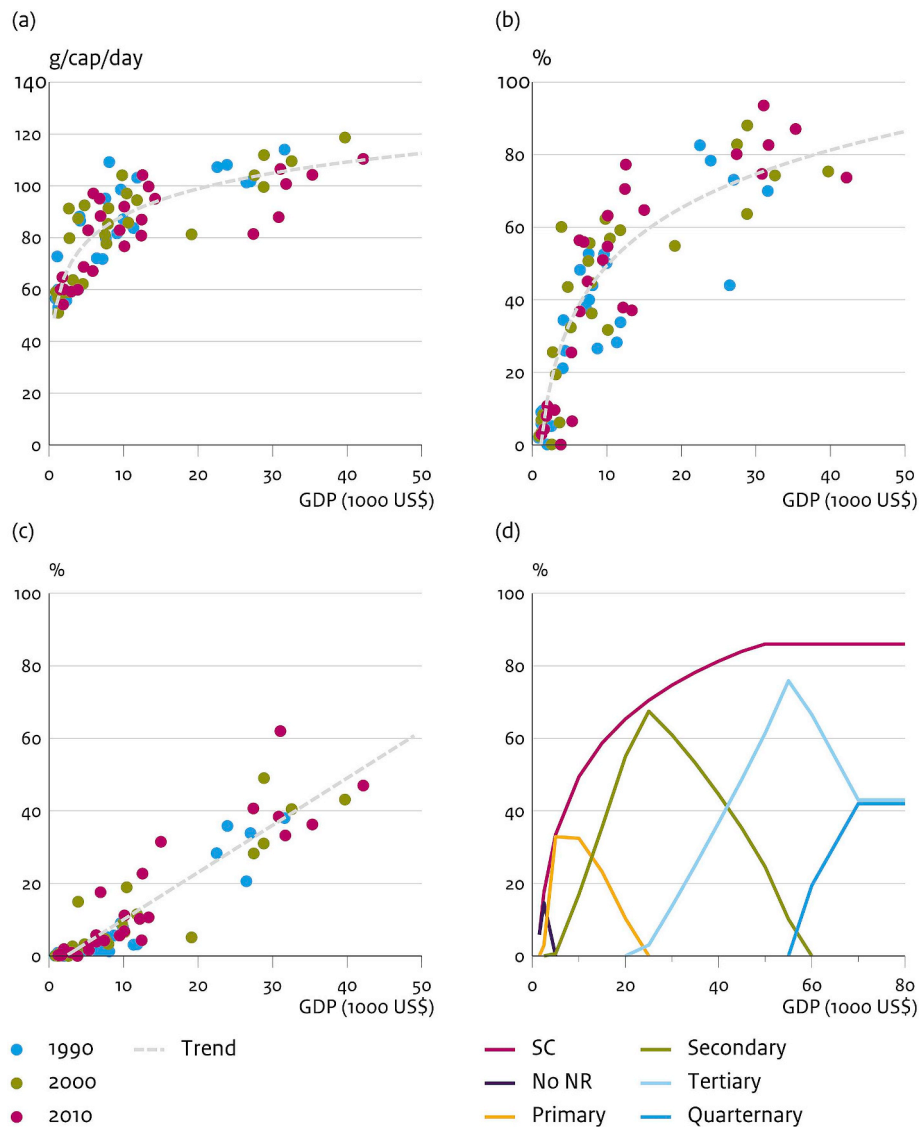


Fig. 2. Relationship between GDP and (a) protein consumption ($R^2 = 0.73$), (b) sewerage connection (SC; $R^2 = 0.81$) and (c) nutrient removal (NR; $R^2 = 0.85$) for image regions and (d) change in SC and NR for a hypothetical country in the SSP2 world moving from low GDP to high GDP. The equations for the years 1990, 2000 and 2010 separately and for all years together are nearly equal. Protein consumption and sewerage connection are described with a logarithmic regression model and nutrient removal with a linear (S.I. 5).

Table 2

Nitrogen, phosphorus (NR^N and NR^P) and overall nutrient removal fraction (NR^{NP}) for primary, secondary, tertiary and quaternary waste water treatment.

	Primary	Secondary	Tertiary	Quaternary
NR^N	0.1	0.35	0.8	0.95
NR^P	0.1	0.45	0.9	0.95
NR^{NP}	0.1	0.4	0.85	0.95

ammonium volatilization and both nutrients are reduced by agriculture recycling. The estimates for local agricultural nutrient recycling were taken from Morée et al. (2013). The remaining part was split into a urine part of 80% N and 62% P which is discharged to surface water and a feces part which is locally accumulated in soil or groundwater.

2.3. Scenario-specific input data

Table 1 gives a brief description of each of the five SSPs in terms of total and urban population, GDP and other qualitative aspects, such as sustainability, environmental goals, equality and technology. Future

protein consumption is calculated from per-capita GDP with an equation that is common to all SSPs (Fig. 2a):

$$\text{protein consumption} = 14.907 \ln(\text{GDP}) - 48.767 \quad (2)$$

The equations for calculating future SC and NR (Fig. 2b and c) have scenario-specific factors. For SC the equation is as follows:

$$SC = f_{SC_{\text{scenario}}} * (22.969 \ln(\text{GDP}) - 162.12 + f_{SC_{\text{country}}}) \quad (3)$$

where $f_{SC_{\text{scenario}}}$ is a scenario-specific multiplier (Table 3), and $f_{SC_{\text{country}}}$ is the country-specific correction to match calculated values to the data for 2010 (Fig. 2b). The maximum overall SC depends on the fraction of the rural population with a sewerage system connection, which has a maximum value of 10%–50%, depending on the SSP (Table 3). Finally, NR is calculated according to:

$$NR = \min(f_{NR_{\text{scenario}}} * (0.0013 * \text{GDP} - 2.9578 + f_{NR_{\text{country}}}), SC * NR_{\text{max}_{\text{scenario}}}) \quad (4)$$

Where $f_{NR_{\text{scenario}}}$ is a scenario-specific multiplier, $f_{NR_{\text{country}}}$ the country-specific correction to match the result of Equation (4) with data

Table 3

Scenario specific coefficients for 2050. Coefficient values are linearly interpolated between 2010 and 2050.

		2010	SSP1	SSP2	SSP3	SSP4	SSP5
f_{SC}	Fraction sewerage connection	1	1.1	1.0	0.9	0.95	1.05
f_{NR}	Fraction nutrient removal	1	1.1	1.0	0.9	0.95	1.05
f_{rural}	Fraction rural connection	0	0.5	0.3	0.1	0.1	0.5
f_{NR_max}	Maximum percent nutrient removal (%)	85	95	90	85	85	95

for 2010, and f_{NR_max} is the maximum achievable nutrient removal fraction which varies per scenario (Table 3). In SSP1, with good progress towards sustainable goals and SSP5 with rapid technological development, this maximum removal is 95% assuming that quaternary treatment is added to tertiary wastewater treatment plants. This high level of nutrient removal is already achieved for N and P in some countries, for example in Germany (EEA, 2014). We therefore used this level of nutrient removal as a maximum achievable removal fraction for SSP1 and SSP5 with somewhat lower values in the other SSPs (Table 3). Countries with a GDP below US dollars 2500 are assumed to have no wastewater treatment or a stable treatment level from 2010 onwards.

Overall nutrient removal needs to be translated to the four types of wastewater treatment. Since wastewater treatment plants have a lifetime of 30 years or more, the situation in 2010 is the basis for calculating the situation in 2020, and this result was used for 2030, and so on. Countries with a low GDP are supposed to build primary treatment plants while countries with a high GDP build tertiary treatment plants. In western Europe, primary wastewater treatment plants were extended with secondary treatment and later, with tertiary treatment installations. This process was modelled for each country, for year t , in three steps: (i) the percentage of sewerage system connection and access to the various types of treatment systems in year $t-10$ was used as a starting point; the treatment type with highest percentage being the dominant one; (ii) for year t , first, additional nutrient removal ($NR_t - NR_{t-10}$) was achieved by reducing the percentage untreated sewage and increasing the level of the dominant type; (iii) if the first two steps did not yield the required overall nutrient removal level, first primary treatment was upgraded to secondary treatment, next, secondary to tertiary and, finally, tertiary to quaternary treatment to arrive at the required overall nutrient removal level. Using this stepwise iterative approach, we modelled the successive upgrade of treatment levels as demonstrated for a hypothetical country with increasing GDP (Fig. 2d).

The use of P-free detergents is currently regulated by environmental policies in the EU, United States and certain other countries. In the scenarios, we distinguished reactive environmental policies (in SSP3 and SSP4) and proactive environmental policies (in SSP1); in the SSP2 scenario (business-as-usual) and in SSP5, attitudes towards the environment are assumed to be less proactive than in SSP1. Banning detergents with a high P content is implemented in the 5 scenarios for 2050, using the following criteria: (i) in SSP1, all countries with a GDP of more than USD 20,000 per capita in 2050 will have full penetration of P-free detergents; (ii) in SSP2, all countries with a GDP above USD 40,000 per capita in 2050 will have full penetration of P-free detergents; (iii) in SSP3, standard P containing detergents will still be permitted in 2050; in countries currently using P-free detergents, half of the detergent use will consist of P-free detergents in 2050; (iv) in SSP4, with less environmental policy, the level of penetration of P-free detergents is between that in the current situation and in the SSP2 scenario for 2050; (v) in SSP5, all countries with a GDP of more than USD 30,000 per capita in 2050 will have full penetration of P-free detergents. In all other cases, we assumed the use of P-based laundry and dishwasher detergents. The use of P-free detergents for years between 2010 and 2050 was obtained by linear interpolation.

2.4. Sustainable Development Goals and recycling potential

In the SDG 6.3.2, waste water that is safely treated is defined as the sum of i) sewer and septic tank content treated in at least a primary wastewater treatment plant, and ii) pit latrines and composting toilets whereby the waste is disposed in situ (excreta remains safely buried when pit latrine is full) (WHO, 2016). The percentage of pit latrines whereby the waste is safely disposed in situ was obtained from recent data from JMP (WHO and Unicef, 2017a), which were aggregated to IMAGE 27 regions (S.I. 1). The fraction safely treatment in the scenarios is calculated as the sum of the calculated percentage wastewater treatment and the fraction safely disposed of in situ.

The construction of sewerage systems and wastewater treatment facilities provides opportunities to recycle the nutrients contained in the waste water. In this study, we quantified the amounts of N and P on the basis of the projected number of future inhabitants with a sewerage system connection, in both urban and rural areas. This recycling is assumed to occur in SSP1 and SSP5, the scenarios with the most progress towards sustainability and with rapid technological development.

2.5. Sensitivity analysis

Since many model parameters are uncertain, a sensitivity analysis was performed to select the most important model parameters in terms of their effect on N and P discharge for the year 2010, and for 2050 for the five SSPs. This was done using Latin hypercube sampling (LHS) (Saltelli et al., 2000), using default ranges prescribed for each parameter (Morée et al., 2013). LHS can be used in combination with linear regression to quantify the uncertainty contributions of the input parameters to the model outputs. We performed 1000 runs for 2010 and 2050, for five SSPs. Standardised regression coefficients (SRCs) were computed for combinations of input parameter and the model output N and P discharge.

3. Results

3.1. Connection to sewerage system and wastewater treatment

The part of the global population with an SC increased from 21% to 36% between 1970 and 2010, which is a threefold increase from 780 million to 2.5 billion (Table 4). Despite this improvement, the number of people without such a connection increased by a factor of 1.5. Under the scenarios, sewerage connections will increase in all regions, both in percentages and in absolute levels (Figs. 3 and 4). Up to 2050, the number of people with an SC will increase from 2.5 billion to between

Table 4

Global population in million inhabitants with and without SC and population with access to the different types of waste water treatment, overall nutrient removal NR^{NP} , and global emissions of N and P for 1970, 2010 and 2050 for the five SSPs.

	1970	2010	SSP1	SSP2	SSP3	SSP4	SSP5
No SC	2915	4434	2160	3579	5375	4225	1990
SC	779	2456	6317	5602	4588	4911	6585
Wastewater treatment							
Primary	183	860	709	1043	1305	817	447
Secondary	144	567	2773	2780	2086	2197	2363
Tertiary	5	508	1972	1413	1035	1702	1720
Quaternary	0	0	838	303	0	0	2036
NR^{NP} (%)	2	11	43	29	19	26	51
Emissions (Tg)							
N (% change since 2010)	5.2	10.4	15.7 (+50)	16.9 (+62)	15.8 (+51)	17.9 (+71)	13.4 (+29)
P (% change since 2010)	0.8	1.5	1.7 (+17)	2.4 (+63)	2.4 (+68)	2.4 (+68)	1.6 (+11)

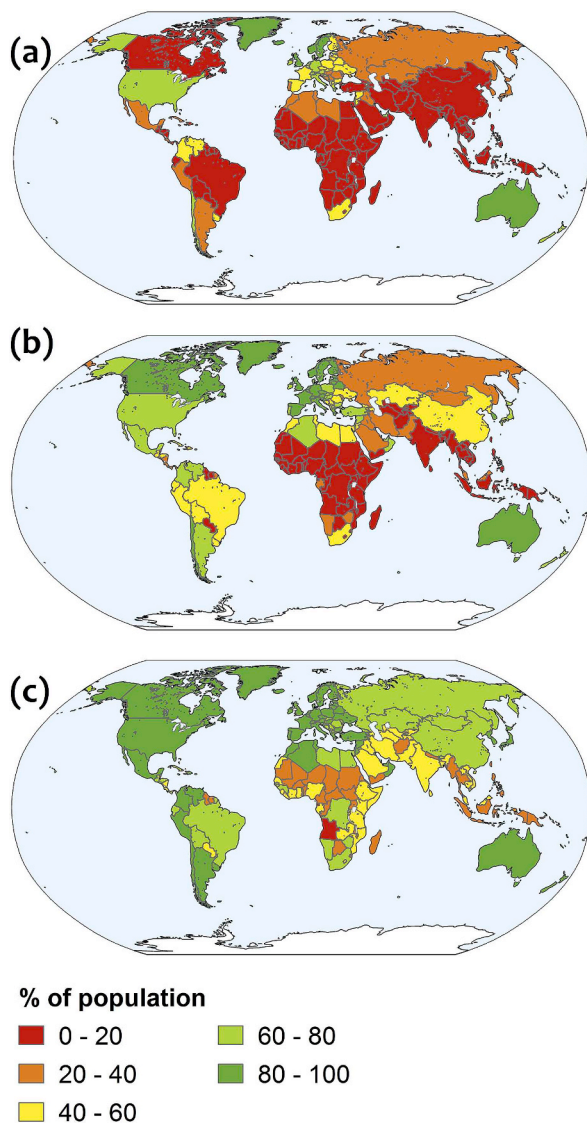


Fig. 3. Sewerage connection per country in 1970 (a), 2010 (b) and 2050 (c) for the SSP2 scenario.

4.6 and 6.6 billion.

Results are aggregated to the level of 10 world regions (S.I. 1). In most regions, the number of people without an SC will decrease, except in SSP3 where it will increase by 20% (Fig. 4, SI. 2). In SSP2 and SSP4, the number of people without an SC will increase in Africa and the Middle East, as a result of the rapidly growing population. The largest increases in the number of people connected to a sewerage system will take place in South Asia and China, followed by sub-Saharan Africa and Southeast Asia. For South Asia, the number of inhabitants with an SC will increase from 160 million people today to between 0.9 and 1.3 billion by 2050.

In 1970, in Europe, wastewater treatment was limited to primary treatment (Fig. 4). By 2010, already 28% of the global population had access to some type of wastewater treatment. For 2050, between 44% (SSP3) and 74% (SSP1) is projected to have access to wastewater treatment. Primary treatment is the most common type of treatment in sub-Saharan Africa, secondary treatment is most common in Southeast Asia and tertiary treatment in the other regions. With the availability of new technology, quaternary treatment will start to play a role in high-income countries, in SSP1, SSP2 and SSP5.

3.2. Discharge to surface water

Nutrient discharge to surface water increased from 5.2 to 10.4 Tg N yr^{-1} and from 0.8 to 1.5 Tg P yr^{-1} , respectively, between 1970 and 2010, and will increase further to 13.4–17.9 Tg N yr^{-1} and 1.6–2.4 Tg P yr^{-1} by 2050, in the SSPs (Table 4, Fig. 5). Up to 2030, the increase in nutrient discharge under SSP5 will be 50% for N and 35% for P, whereas for the subsequent period up to 2050, it is projected to decrease, but not below 2010 levels (Fig. 5). In SSP1, N discharge will increase over the whole scenario period up to 2050, while P discharge will increase up to 2030, followed by a slight decrease until 2050. In the other SSPs, nutrient discharge levels will continue to increase up to 2050.

The largest increases are projected for sub-Saharan Africa (by a factor of 4–8) and South Asia (by a factor of 3–5) (Fig. 4, SI. 2, 4). Between 2010 and 2050, the combination of population growth, urbanization and income growth in sub-Saharan Africa will result in an increase in people with a sewerage system connection, from 9 times more people in SSP3 and SSP4 to 16 times more people in SSP1 and SSP5; for SSP2, the results will be somewhere in-between. Despite the higher levels of nutrient removal in SSP1 and SSP5, the increase in the sub-Saharan population will not be compensated by more removal of nutrients in treatment plants, and total discharge to surface water will still increase over the whole period up to 2050.

In North America, Western and Central Europe, Russia and Central Asia, Japan and Oceania, the SSP1, SSP2, SSP4 and SSP5 scenarios show decreasing or stable nutrient discharge, while in SSP3 the discharge level will increase slightly towards 2050 (Fig. 4, SI. 2). These differences are the result of different levels of wastewater treatment with relatively stable population levels. Under SSP3, the combination of the smallest population size with the lowest level of nutrient removal, for these regions, results in the highest levels of nutrient discharge. Projections for Central and South America show future decreases ranging from 5% for N and 40% for P in SSP5, to increases by 50% in SSP3. Population size in the China region is more or less the same under all scenarios (Fig. 4), with a peak in 2020–2030, while GDP is projected to increase between 2010 and 2050 by a factor of 6–9 (S.I. 2). In SSP1 and SSP5, there is a shift towards advanced, quaternary treatment in this region, due to rapid GDP growth, and this will reduce nutrient discharge to a third of the current levels, while under the other SSPs, the discharge level remains stable from 2010 onwards.

Differences between the SSPs in projected discharge levels are the highest in sub-Saharan Africa, closely followed by South Asia, whereas in Europe, North America, Japan and Oceania, differences vary between 40% and 80% (Fig. 4, SI. 2). For most regions except sub-Saharan Africa, the highest discharge levels are seen in SSP3, and the lowest in SSP5. For sub-Saharan Africa, SSP1 and SSP5 show the largest increases in nutrient discharge from waste water, and SSP3 shows the smallest (Fig. 4).

3.3. Sensitivity analysis

We discuss model significant parameters with SRC values of < -0.2 or > 0.2 (which is an important contribution of $> 4\%$ to model output) for global N and P discharge (S.I. 3). For all years and all scenarios, total population (SRC = 0.40 for N and 0.36 for P in 2010), sewerage connection (SRC = 0.38 for N and 0.53 for P in 2010), parameters related to food consumption (protein consumption, N in proteins and P:N ratio in food) (e.g. SRC for protein consumption is 0.38 for N and 0.21 for P in 2010) and urban population (0.22 for N and not important for P in 2010) were the most important parameters (both significant and with an SRC of greater than 0.2), which together determine the total human nutrient input to sewerage systems. This is completely in line with the results of the sensitivity analysis for the year 2000 presented by Morée et al. (2013). The SRC values for N and P discharge for the total

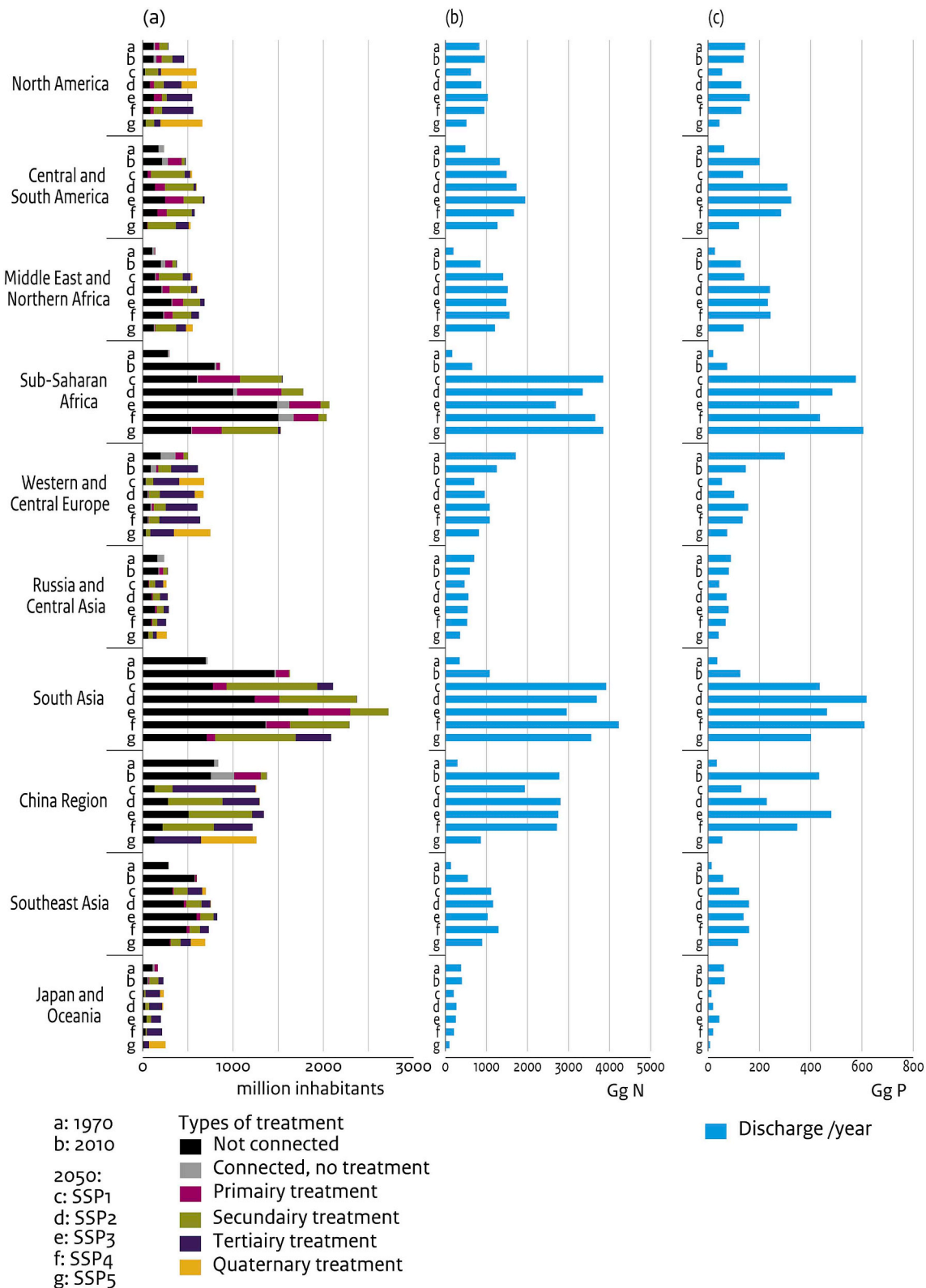


Fig. 4. Number of inhabitants lacking a sewerage connection, with a connection to sewerage systems and without access to wastewater treatment and with access by treatment type for 1970, 2010 and 2050 for the five SSPs for 10 world regions (a), nitrogen (b) and phosphorus (c) discharge to surface water.

population and urban population, under the scenarios for 2050 are comparable to those in 2010. SRC values for sewerage connections are lower than those of 2010 under SSP1 and SSP5 (due to more efficient nutrient removal and thus lower discharge levels per capita), while under SSP3 the SRC values exceed those of 2010. The removal of

nutrients in advanced treatment systems (tertiary and quaternary) are also important (significant and with an SRC of less than -0.2) processes that strongly reduce nutrient flows.

We recognize that there are regional differences. For example, in countries where a large fraction of households has a laundry machine

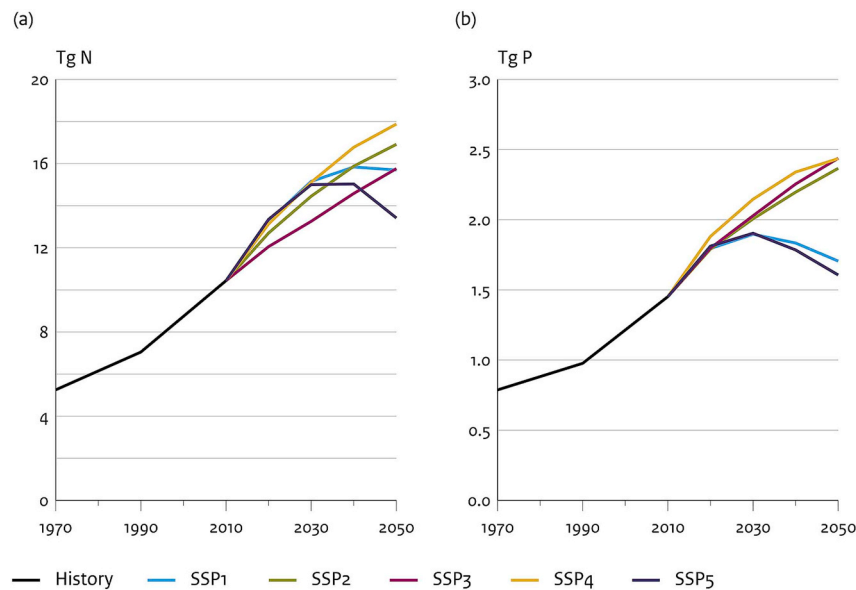


Fig. 5. Global nitrogen (a) and phosphorus (b) discharge to surface water for the period 1970–2010 for the five scenarios.

and dishwasher, a change in detergent use or use of P-free detergents will have a larger impact on the P discharge to surface water than in countries where the use of such machines is less prevalent. Also, in countries without advanced treatment plants, increases in the N or P removal efficiency will have a smaller effect on discharge levels than in countries with full access to advanced treatment systems.

3.4. Recycling of nutrients in agriculture

In 2010, the recycling of nutrients in agricultural production systems had globally been reduced to 2%, but the construction of sewerage systems and wastewater treatment facilities in the future offers possibilities for more nutrient recycling. We investigated the options for recycling under SSP1 and SSP5, with 4 billion people newly connected to a sewerage system between 2010 and 2050, resulting in an increase in the volume of nutrients in sewage effluent average by an average factor of 2.7 (Table 5). Assuming that all new houses and future construction of sewerage systems would include separate urine collection and diversion systems, this would allow for recycling of 15 Tg N yr⁻¹ and 1.2 Tg P yr⁻¹ in SSP1, and 17 Tg N yr⁻¹ and 1.3 Tg P yr⁻¹ in SSP5. With increasing income levels and population growth, household and retail losses will also increase by 2.5 Tg N yr⁻¹ and 0.25 Tg P yr⁻¹. In the rural area, about 80–100 million people will be connected to sewerage systems, from which the sewage could also be collected and recycled.

4. Discussion

For this paper, we used recent, global information on connections to sewerage systems and wastewater treatment (WHO and Unicef, 2013; OECD, 2016; UN, 2017; WHO and Unicef, 2017a) to produce an update of the input data of the previous model version (Morée et al., 2013). Parallel to the updating of the data on sewerage connection and nutrient removal, we were also able to validate the data that originated from Van Drecht et al. (2009). For most countries, estimated total treatment according to Van Drecht et al. (2009) for 2000 was comparable with data from UN (2017) and Reder (2017), whereby for some countries a correction was needed (S.I. 6). However, for several countries, the data on the level of wastewater treatment are less certain than on the connection to sewerage systems. Other uncertainties in the calculated nutrient discharge include variability in the nutrient removal efficiency for the various types of wastewater treatment, agricultural recycling and the ‘other’ fates of nutrients (Fig. 1). A source of P that has been ignored due to a lack of data is the addition of orthophosphate to drinking water (between 1 and 2 mg P/l) to reduce lead concentrations in tap water (WHO, 2011; Comber et al., 2013).

The total discharge for the year 2000 is estimated by Morée et al. (2013) at 7.7 Tg N yr⁻¹ and 1.0 Tg P yr⁻¹, which is slightly below our estimates of 8.4 Tg N yr⁻¹ and 1.1 Tg P yr⁻¹. A recent study (Mekonnen and Hoekstra, 2017), which was largely based on the studies by Van Drecht et al. (2003) and Morée et al. (2013), calculates an even lower total discharge of 0.9 Tg P yr⁻¹ for the year 2000. The differences are

Table 5

Total global population with a connection to sewerage systems in urban and rural areas, household and retail waste fluxes, and sewage influent for 2010 and the increase between 2010 and 2050 for SSP1 and SSP5 to demonstrate the effect of possible options for recycling nutrients.

Population in million people	2010		SSP1		SSP5	
Urban population with sewerage connection	2367		+ 3763		+ 4029	
Rural population with sewerage connection	89		+ 98		+ 100	
Nutrient fluxes (Tg yr ⁻¹)	N, 2010		P, 2010		N, SSP5	
Household and retail losses	4.5	0.4	+ 2.3	+ 0.2	+ 2.7	+ 0.3
Emission from households	10.9	1.7	+ 21.3	+ 2.1	+ 23.8	+ 2.6
Nutrients in urine (80% N, 62% P)	7.7	0.6	+ 15.2	+ 1.2	+ 17.0	+ 1.3
Nutrients in feces (20% N, 38% P)	1.9	0.3	+ 3.8	+ 0.7	+ 4.2	+ 0.8
Loss from sewer pipes	1.2	0.2	+ 2.3	+ 0.2	+ 2.6	+ 0.3
Detergents		0.6		+ 0.0		+ 0.2

Table 6

Treated wastewater (%) in 2010, 2030 and 2050 for the five SSPs, and the SDG target for 2030. Bold shaded values indicate scenario-years for which the SDG target is not met.

	2010	SDG target	SSP1		SSP2		SSP3		SSP4		SSP5	
			2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
North America	73	87	93	99	88	93	83	83	87	91	92	99
Central and South America	44	72	76	93	71	80	65	67	68	75	76	94
Middle East and Northern Africa	41	71	67	81	62	72	57	60	61	70	68	84
Sub-Saharan Africa	18	59	36	74	29	54	26	35	25	31	37	78
Western and Central Europe	83	91	95	100	92	97	88	90	91	97	95	100
Russia and Central Asia	47	74	71	88	66	77	62	66	66	75	72	90
South Asia	23	61	49	76	44	61	40	46	42	54	50	79
China Region	46	73	95	100	86	98	76	81	88	100	95	100
Southeast Asia	33	67	59	83	55	70	52	58	54	64	61	87
Japan and Oceania	89	94	96	99	95	98	94	94	95	96	96	99
Global	42	71	67	86	61	74	56	58	60	65	68	88

caused by including households without a sewerage system connection in our updated approach. On a smaller scale, our results show good agreement with Dutch national statistics for 1990, 2000 and 2010, for both nutrients (CBS et al., 2017).

For all years and all scenarios, total population, urban population, protein consumption and sewerage connection were the most important (both significant and with an SRC of > 0.2) parameters determining the total human nutrient input to sewerage systems. Nutrient removal in advanced treatment systems (tertiary and quaternary) consists of processes that strongly reduce nutrient flows.

Our results show that global nutrient discharge to surface water will increase under all SSPs. In industrialized countries with slow population growth, such as Europe, Russia and Central Asia, North America, China, Japan and Oceania, further improvement in wastewater treatment to at least tertiary treatment will reduce or stabilize nutrient discharge (S.I. 4). By contrast, in sub-Saharan Africa and South and Southeast Asia, rapid population growth and urbanization in combination with lagging development of wastewater treatment results in dramatic increases in nutrient discharge under all SSPs.

The construction of new sewerage systems and wastewater treatment plants is projected to occur more rapidly under SSP1 and SSP5 than under the other scenarios, which, for most regions results in lower nutrient emission levels. Sub-Saharan Africa shows a different pattern, with low incomes and either no wastewater treatment or only primary treatment in 2010. For 2050, SSP1 and SSP5 projects highest SC and NR and SSP3 projects lowest of both. In combination with the growth of the population, SSP1 and SSP5 project the highest nutrient emission levels, while SSP3 projects the lowest levels. The investments in sewerage systems help to reduce human health problems, but without appropriate wastewater treatment, result in more emissions to the ecosystems.

Nutrient emission levels start to decline after 2040 under SSP1 and SSP5. This is a result of high economic growth in both scenarios and is in line with the storylines whereby SSP1 has progress towards sustainability and SSP5 has rapid technological development. Advanced, large-scale quaternary treatment may lead to decoupling of population growth and nutrient discharge. This also allows recycling nutrients for agricultural use. Several recent studies on nutrient recycling fail to quantify the amount of N and P that can be recycled (Cordell et al., 2011; Miheleic et al., 2011; Roy, 2017). In this study, options to recycle nutrients were quantified on the basis of the increase in urban development. We recognize that more N and P could be collected if existing sewerage systems would be adapted or replaced, for example with systems that have separate urine collection.

Development of wastewater treatment installations could also occur more rapidly than in our scenarios, where we assumed a fixed sequence from no treatment to primary, then secondary and tertiary, and finally,

in SSP1 and SSP5, quaternary. However, other more direct routes are also possible.

This scenario analysis indicates that it is difficult to achieve the SDG 6.3 (71% safely treated waste water by 2030) (Table 6). This objective is not achieved by 2030 under any of the SSPs, although SSP1 and SSP5 show good progress and would achieve this SDG just after 2030, and under SSP2 by 2050. Under SSP3, SDG 6.3 will be achieved by 2050 in Western and Central Europe, China, Japan and Oceania. Especially in sub-Saharan Africa and South Asia, the level of treatment will be insufficient under nearly all scenarios. The difficulties that countries have in achieving SDG 6.3 are manifold, and are mainly related to poverty, poorly functioning institutions and inequality (WHO and Unicef, 2017b). For example, although there is progress in improving sanitation in many countries, in 23 low-income countries between 1990 and 2015 there was no improvement or even a decline in the fraction of the population with access to improved sanitation (Alagidede and Alagidede, 2016; Satterthwaite, 2016). Data on 40 cities in sub-Saharan Africa with more than 1 million inhabitants show that most of those cities had minimal or no sewerage systems in place and, often, there was no plan to improve on this situation (Miller and Parker, 2013).

Our results also show that the health situation and the environment in many developing countries, next to increasing the number of people connected to a sewerage system, would require rapid development of wastewater treatment systems, preferably tertiary of more advanced facilities.

5. Conclusions

Our results show that the number of people with a sewerage system connection will increase by 2–4 billion in the coming decades. Despite increased nutrient removal in future wastewater treatment facilities, nutrient levels in waste water will increase by 10%–70% in the 2010–2050 period. Peak nutrient discharge levels will occur under SSP1 and SSP5 in the 2030–2040 period, while under the other scenarios, increases are projected to continue over the full 2010–2050 scenario period. The largest increases in nutrient emissions will take place in sub-Saharan Africa and South Asia, while in the developed countries, emission levels will decrease or stabilize after 2020. The highest nutrient discharge is projected under SSP3 for most world regions except for sub-Saharan Africa. In sub-Saharan Africa are the highest discharge levels projected under SSP1 and SSP5, due to lagging nutrient removal in wastewater treatment systems. Nutrient collection in new urban and rural sewerage systems as assumed in SSP1 and SSP5 may yield substantial amounts of both N and P for recycling in agriculture. These results show that, in developing countries with high population growth, a further deterioration of the water quality may occur if sewerage system connection is not accompanied by adequate

wastewater treatment to remove nutrients. The SDG 6.3 —safely treated waste water by 2030— will be achieved in the developed countries, except for under SSP3 and SSP4, where this goal will not be achieved until 2050. In the developing countries, the goal will be achieved by 2050, under SSP1, SSP2 and SSP5.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.jenvman.2018.10.048>.

References

- Alagidede, P., Alagidede, A.N., 2016. The public health effects of water and sanitation in selected West African countries. *Publ. Health* 130, 59–63.
- Beusen, A.H.W., Bouwman, A.F., Van Beek, L.P.H., Mogollón, J.M., Middelburg, J.J., 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. *Biogeosciences* 13, 2441–2451.
- Bijl, D.L., Bogaart, P.W., Dekker, S.C., Stehfest, E., de Vries, B.J.M., van Vuuren, D.P., 2017. A physically-based model of long-term food demand. *Global Environ. Change* 45, 47–62.
- Billen, G., Garnier, J., Lassaletta, L., 2013. The nitrogen cascade from agricultural soils to the sea: modelling nitrogen transfers at regional watershed and global scales. *Phil. Trans. R. Soc. B Biol. Sci.*, 20130123.
- Bouwman, A.F., Dreht, G.V., Knoop, J.M., Beusen, A.H.W., Meinardi, C.R., 2005. Exploring changes in river nitrogen export to the world's oceans. *Global Biogeochem. Cycles* 19.
- Butcher, R.W., 1947. Studies in the ecology of rivers: VII. The algae of organically enriched waters. *J. Ecol.* 186–191.
- CBS, PBL, RIVM, WUR, 2017. Belasting Van Het Oppervlaktewater Met Vermestende Stoffen, 1990-2015 (Indicator 0192, Versie 18, 2 Oktober 2017). (CBS), Den Haag; PBL Planbureau voor de Leefomgeving, Den Haag; RIVM Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven; en Wageningen University and Research, Wageningen. www.clo.nl.
- Comber, S., Gardner, M., Georges, K., Blackwood, D., Gilmour, D., 2013. Domestic source of phosphorus to sewage treatment works. *Environ. Technol.* 34, 1349–1358.
- Cordell, D., Rosemarin, A., Schröder, J.J., Smit, A.L., 2011. Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. *Chemosphere* 84, 747–758.
- Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321, 926–929.
- EC, 2011. EP Supports Ban of Phosphates in Consumer Detergents. European Commission, Brussels.
- EEA, 2012. European Waters - Current Status and Future Challenges. Synthesis. European Environmental Agency, Copenhagen.
- EEA, 2014. Performance of Water Utilities beyond Compliance. Sharing Knowledge Bases to Support Environmental and Resource-efficiency Policies and Technical Improvements. European Environment Agency, Copenhagen.
- EEC, 1991. Directive 1991/271/EEC Concerning Urban Waste Water Treatment. Brussels.
- EU, 2012. REGULATION (EU) No 259/2012 of the EUROPEAN PARLIAMENT and of the COUNCIL of 14 March 2012 Amending Regulation (EC) No 648/2004 as Regards the Use of Phosphates and Other Phosphorus Compounds in Consumer Laundry Detergents and Consumer Automatic Dishwasher Detergents. European Parliament and of the Council, Brussels.
- FAO, 2017. FAOSTAT Database Collections. Protein Supply Quantity. Food and Agriculture Organization of the United Nations, Rome. <http://www.fao.org/faostat/en/#data/FBS>.
- Gilbert, D., Rabalais, N.N., Díaz, R.J., Zhang, J., 2010. Evidence for greater oxygen decline rates in the coastal ocean than in the open ocean. *Biogeosciences* 7, 2283–2296.
- Grigg, D., 1995. The pattern of world protein consumption. *Geoforum* 26, 1–17.
- Janse, J.H., Kuiper, J.J., Weijters, M.J., Westerbeek, E.P., Jeuken, M.H.J.L., Bakkenes, M., Alkemade, R., Mooij, W.M., Verhoeven, J.T.A., 2015. GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems. *Environ. Sci. Pol.* 48, 99–114.
- Janssen, P.H.M., Heuberger, P.S.C., 1995. Calibration of process-oriented models. *Ecol. Model.* 83, 55–66.
- Jiang, L., O'Neill, B.C., 2017. Global urbanization projections for the shared socioeconomic pathways. *Global Environ. Change* 42, 193–199.
- KC, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Global Environ. Change* 42, 181–192.
- Kemp, W.M., Testa, J.M., Conley, D.J., Gilbert, D., Hagy, J.D., 2009. Temporal responses of coastal hypoxia to nutrient loading and physical controls. *Biogeosciences* 6, 2985–3008.
- Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K.L., Kram, T., Riahi, K., Winkler, H., Van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change* 1–14.
- Leimbach, M., Kriegler, E., Roming, N., Schwanitz, J., 2017. Future growth patterns of world regions – a GDP scenario approach. *Global Environ. Change* 42, 215–225.
- Ligtvoet, W., Hilderink, H., Bouwman, A., van Puijenbroek, P., Lucas, P., Witmer, M., 2014. Towards a World of Cities in 2050. An Outlook on Water-related Challenges. Background Report to the UN-habitat Global Report. PBL Netherlands Environmental Assessment Agency, The Hague.
- Mekonnen, M.M., Hoekstra, A.Y., 2017. Global anthropogenic phosphorus loads to freshwater and associated grey water footprints and water pollution levels: a high-resolution global study. *Water Resour. Res.* 54, 345–358.
- Mihelcic, J.R., Fry, L.M., Shaw, R., 2011. Global potential of phosphorus recovery from human urine and feces. *Chemosphere* 84, 832–839.
- Miller, M., Parker, C., 2013. Sanitation Status of African Cities. Monitoring the Sanitation Status of African Cities, Surrey, United Kingdom.
- Mogollón, J.M., Lassaletta, L., Beusen, A., Grinsven, H. v., Westhoek, H., Bouwman, A.F., 2018. Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways. *Environ. Res. Lett.* 13, 044008.
- Morée, A.L., Beusen, A.H.W., Bouwman, A.F., Willems, W.J., 2013. Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. *Global Biogeochem. Cycles* 27, 1–11.
- NDRC, 2016. The Thirteenth Five Years Plan of Sewage Treatment and Construction of Recycling Facilities in Chinese Cities and County (In Chinese). National Development and Reform Commission, Beijing.
- Nyenje, P.M., Foppen, J.W., Uhlenbrook, S., Kulabako, R., Muwanga, A., 2010. Eutrophication and nutrient release in urban areas of sub-Saharan Africa — a review. *Sci. Total Environ.* 408, 447–455.
- OECD, 2012. OECD Environmental Outlook to 2050. The Consequences of Inaction. OECD, 2016. Water: Wastewater Treatment. OECD Environment Statistics (database).
- O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* 122, 387–400.
- Reder, K., 2017. Large-scale Modeling of Bacterial Contamination in Rivers, to Support the Global Assessment of Pollutant Concentrations in Rivers. University of Kassel, Kassel.
- Roy, E.D., 2017. Phosphorus recovery and recycling with ecological engineering: a review. *Ecol. Eng.* 98, 213–227.
- Saltelli, A., Chan, K., Scott, E.M., 2000. Sensitivity Analysis. John Wiley and Sons, Chichester, U.K.
- Satterthwaite, D., 2016. Missing the Millennium Development Goal targets for water and sanitation in urban areas. *Environ. Urbanization* 28, 99–118.
- SFD, 2017. SFD Promotion Initiative, Dhaka - Bangladesh, Santa Cruz - Bolivia, Bahir Dar - Ethiopia. Sustainable Sanitation Alliance, Lima - Peru.
- Simha, P., Ganesapillai, M., 2017. Ecological Sanitation and nutrient recovery from human urine: how far have we come? A review. *Sustain. Environ. Res.* 27, 107–116.
- Stehfest, E., Vuuren, D. v., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., Elzen, M. d., Lucas, P., Minnen, J. v., Müller, M., Prins, A., 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model Description and Policy Applications. PBL Netherlands Environmental Assessment Agency, The Hague.
- UN, 2015. Transforming Our World: the 2030 Agenda for Sustainable Development. 70/1, United Nations.
- UN, 2017. UN Data - a World of Information. United Nations. <http://data.un.org/Default.aspx>.
- Unicef, WHO, 2015. Progress on Sanitation and Drinking Water. Unicef, World Health Organization, US.
- Van Dreht, G., Bouwman, A.F., Harrison, J., Knoop, J.M., 2009. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. *Global Biogeochem. Cycles* 23, 1–19.
- Van Puijenbroek, P. J. T. M., A. H. W. Beusen, and A. F. Bouwman. Submitted. Global scenarios of the Phosphorus content in laundry and dishwasher detergents. Submitted.
- Van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W., 2010. Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion. *Global Environ. Change* 20, 428–439.
- Van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H., 2014. A new scenario framework for Climate Change Research: scenario matrix architecture. *Climatic Change* 122, 373–386.
- Van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Müller, C. v., Ruijven, B.J., van der Sluis, S., Tabeau, A., 2017a. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environ. Change* 237–250.
- Van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Müller, C., van Ruijven, B.J., van der Sluis, S., Tabeau, A., 2017b. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environ. Change* 42, 237–250.
- WHO, 2011. Guidelines for Drinking-water Quality, fourth ed. World Health Organization, Geneva.
- WHO, 2016. Integrated Monitoring Guide for SDG 6. Step-by-step Monitoring Methodology for 6.3.1 - Work in Progress to Be Revised Based on Country Feedback. World Health Organization V1 21 Oct 2016.
- WHO, Unicef, 2013. Progress on Sanitation and Drinking-water. 2012 Update WHO/

- Unicef Joint Monitoring Programme for Water Supply and Sanitation. WHO, Unicef, Geneva, Switzerland.
- WHO, Unicef, 2015. Joint Monitoring Program (JMP) for Water Supply and Sanitation. Geneva, Switzerland.
- WHO, Unicef, 2017a. Joint Monitoring Programme for Water Supply, Sanitation and Hygiene. Estimates on the Use of Water, Sanitation and Hygiene by Country. (2000–2015).
- WHO, Unicef, 2017b. Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines. Licence: CC BY-NC-SA 3.0 IGO. World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), Geneva.
- Wielemaker, R.C., Weijma, J., Zeeman, G., 2018. Harvest to harvest: recovering nutrients with new sanitation systems for reuse in urban agriculture. *Resour. Conserv. Recycl.* 128, 426–437.
- World Bank, 2016. Fecal Sludge Management: Diagnostics for Service Delivery in Urban Areas. P146128. World Bank, Washington.
- Zhang, X.J., Chen, C., Ding, J.Q., Hou, A., Li, Y., Niu, Z.B., Su, X.Y., Xu, Y.J., Laws, E.A., 2010. The 2007 water crisis in Wuxi, China: analysis of the origin. *J. Hazard Mater.* 182, 130–135.