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Health, nutrients and water quality

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pbl.nl/future-water-challenges

Main messages

- Waterborne diseases, each year, result in 780,000 global deaths due to diarrhoea and cholera.
- Socio-economic projections for 2050 assume that an additional 2 to 4 billion people will be connected to sewerage systems. This calls for a major investment in urban infrastructure.
- These scenarios project that primary wastewater treatment will increase from 28% of households today to at least 60% by 2050.
- Under all scenarios, nutrient discharges from households will increase globally by 70%. In Sub-Saharan Africa and South Asia, emission levels will be even 4 to 6 times higher than they are currently.
- In 2010, nutrient discharges from agriculture were 3.8 times higher than those from households, but discharges from households are projected to increase much faster.
- Global emissions to oceans and coastal seas will increase up to 2050 and result in further eutrophication and cyanobacterial blooms in the latter.

1.1 Introduction

1.1.1 Overview

Waterborne diseases are responsible for very high mortality in many developing, poor countries. These diseases are mainly due to the lack of improved sanitation. The main option to improve health is to construct sewerage systems to remove human waste from households. This negatively affects ecosystems, when surface waters become to greatly polluted by discharges of untreated organic waste. Wastewater treatment will reduce these high loads, first with a reduction of the organic waste and next with a reduction of the discharge of nutrients. The other loads of nutrients onto surface water are diffuse discharges from agriculture due to high fertiliser use. The combination of nutrient discharges from agriculture and households results in eutrophication, leading to the massive growth in algae and water plants in freshwater and marine water systems, poisoned drinking water, massive fish kill in aquaculture, and less tourism due to algae blooms (Diaz and Rosenberg, 2008; Glibert et al., 2005).

The Sustainable Development Goals (SDGs), the follow-up of the Millennium Development Goals, include goals for sanitation and water quality (SDG 6) (UN, 2015):

- SDG 6.2. ‘by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation’ (UN, 2015).
- SDG 6.3. ‘by 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater’ (UN, 2015).

Other goals with related targets are:

- SDG 3.3. By 2030, combat waterborne diseases.
- SDG 14.1. By 2025, significantly reduce marine pollution including nutrient pollution.
- SDG 15.1. By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.

The objective of this background document is to provide an overview of global sanitation developments and nutrient emissions from households and agriculture. This includes the emissions to coastal seas. The models to calculate the emissions of nutrients are explained. This background document presents results from the chapters on ‘Water pollution and human health’ and ‘Ecological quality of aquatic ecosystems’ from the book *The Geography of Future Water Challenges* (GFWC) (PBL, 2018).

1.1.2 Improvements in sanitation, drinking water and household emission levels

Improved drinking water and sanitation are internationally defined concepts with international targets. Improved drinking water is piped water on premises, including piped household connections inside residential housing and basic drinking water facilities, which means that improved drinking water is available within 15 minutes walking distance (Unicef and WHO, 2015). The access to improved drinking water is increasing in all regions, globally (Table 1). Nevertheless, the drinking water for 159 million people around the world is currently still coming directly from surface water sources.

Improved sanitation facilities are those designed to hygienically separate excreta from human contact and include flush/pour-flush toilets connected to piped sewerage systems, septic tanks or pit latrines, ventilated improved pit latrines, composting toilets or pit latrines with slabs. Unimproved sanitation includes the use of pit latrines without a slab or platform, hanging latrines or bucket latrines and open defaecation, such as disposal of human faeces in fields, forests, bushes, open bodies of water, beaches or other open spaces, or with solid waste. Facilities that are shared by more households are categorised as improved sanitation.

Improved sanitation can be further categorized into basic sanitation and safely managed sanitation. Safely managed sanitation is improved sanitation where excreta are safely disposed of in situ or transported and treated offsite; basic sanitation is improved sanitation without proper treatment of the content of septic tanks and effluent sewer systems.

There is a major contrast between urban and rural sanitation. Globally, 83% of the urban population has improved sanitation compared with only 51% of the rural population. Access to improved sanitation is also determined by the gap between the rich and the poor both within and between countries. Most developed countries have fully improved sanitation systems, while the least developed countries barely have such systems, and the poorest part of their population barely has access to improved sanitation.

Improved sanitation generally includes sewerage systems with flush toilets. In regions with improved sanitation, 80% of the population in cities has access to a sewerage system, compared with 20% in rural areas. The construction of sewerage systems is an improvement to sanitation. Without wastewater treatment, however, a deterioration of water systems often results, due to the direct discharge of organic and nutrient loads into these water systems. Wastewater treatment is essential to reduce the organic and nutrient loads to surface water. SDG 6.3, defined in relation to wastewater treatment, is to halve the amount of untreated waste water. A major increase in the nutrients that are emitted to surface water is to be expected when improved sanitation for all—in cities mostly realised in the form of sewerage systems—is achieved in combination with treating at least half of all the waste water.

The percentage of people with access to improved sanitation is lower than that with access to improved drinking water. Especially in Sub-Saharan Africa, the majority of the population does not have access to improved sanitation, and progress is slower for sanitation than for clean drinking water.

Table 1. Part of the population (in percentages) with access to improved drinking water and improved sanitation, in five regions, in 2000, 2010 and 2015 (WHO and Unicef, 2017) (GFWC, p. 39).

	Access to improved drinking water			Access to improved sanitation		
	2000	2010	2015	2000	2010	2015
Developed Countries	72	99	99	89	97	97
Latin America and the Caribbean	91	94	96	75	82	85
North Africa, the Middle East and Russia	89	92	94	86	89	90
Sub-Saharan Africa	45	54	58	25	27	29
South Asia and East Asia Pacific	79	88	91	44	56	62
World	76	87	89	57	66	69

Household emissions and agricultural diffuse loads are the main source of nutrients to aquatic ecosystems. The main drivers of household emissions are the growth of the population, the growth of the economy and the functioning and organisation of the government with respect to building sewerage systems and wastewater treatment plants. A growth of the economy results in an increase in food consumption, which results in an increase in human waste production and more sewerage systems. Both result in higher nutrient loads. With a further growth of the economy, wastewater treatment plants can be built, resulting in a lower discharge of nutrients. The fate of human waste and nutrient emissions are calculated with IMAGE–GNM (Global Nutrient Model).

1.1.3 Waterborne diseases

The fate of human waste is related to the sanitation level (WHO and Unicef, 2017) and has a major impact on human health (WHO, 2009) and water quality (Beusen et al., 2016; EEA, 2010). The main waterborne diseases are cholera and diarrhoea (WHO, www.who.int, downloaded 3 July 2017). The main causes of waterborne diarrhoea are polluted drinking water, basic piped water on premises, unimproved sanitation, as well as household use of water that has become contaminated/polluted even though it has been filtered or boiled (WHO and Unicef, 2017).

Diarrhoea is the main waterborne disease with yearly 685,000 deaths globally due to inadequate drinking water and inadequate sanitation (Prüss-Ustün et al., 2014). Insufficient hygiene and washing hands without soap are also important reasons, leading to 150,000 deaths. Cholera is the second waterborne disease in the world. It is an endemic disease in many countries, but also has epidemics in countries with a disorganisation or malfunction of the sanitation system. Two countries with recent, severe epidemics are Haiti and Zimbabwe. In Zimbabwe, a cholera epidemic between August 2008 and July 2009 caused 100,000 cases and 4,287 deaths (Mukandavire et al., 2011). This cholera epidemic also affected neighbouring countries such as South Africa, Botswana, Mozambique and Zambia (Mason, 2009). Endemic cholera is widespread and estimates indicate its presence in 69 countries, with 2.9 million cases and 95,000 deaths (Ali et al., 2015), including 2,500 deaths in Haiti due to a cholera outbreak after the earthquake. WHO reported 170,000 cases of cholera, worldwide, with 1,300 deaths in 2015 (WHO, 2016), which is lower than reported by Ali et al. (2015) because not all cholera deaths are reported.
Therefore, the number of waterborne deaths between 1980 – 2015 was yearly around 685,000 due to diarrhoea and 95,000 due to cholera, which results in a total of 780,000 deaths due to waterborne, sanitation- and drinking-water-related diseases (GFWC, pp. 14, 38).

1.1.4 Introduction agricultural emissions

Compared with nutrient emissions from households, nutrient emissions from agriculture due to high loads of fertiliser are a more important driver of water pollution. The productivity of soils strongly depends on the availability of nutrients—especially phosphorus (P) and nitrogen (N)—organic matter content and water availability. As nutrient availability is a limiting condition for crop production, the use of mineral fertilisers has enabled farmers worldwide to vastly increase crop yields.

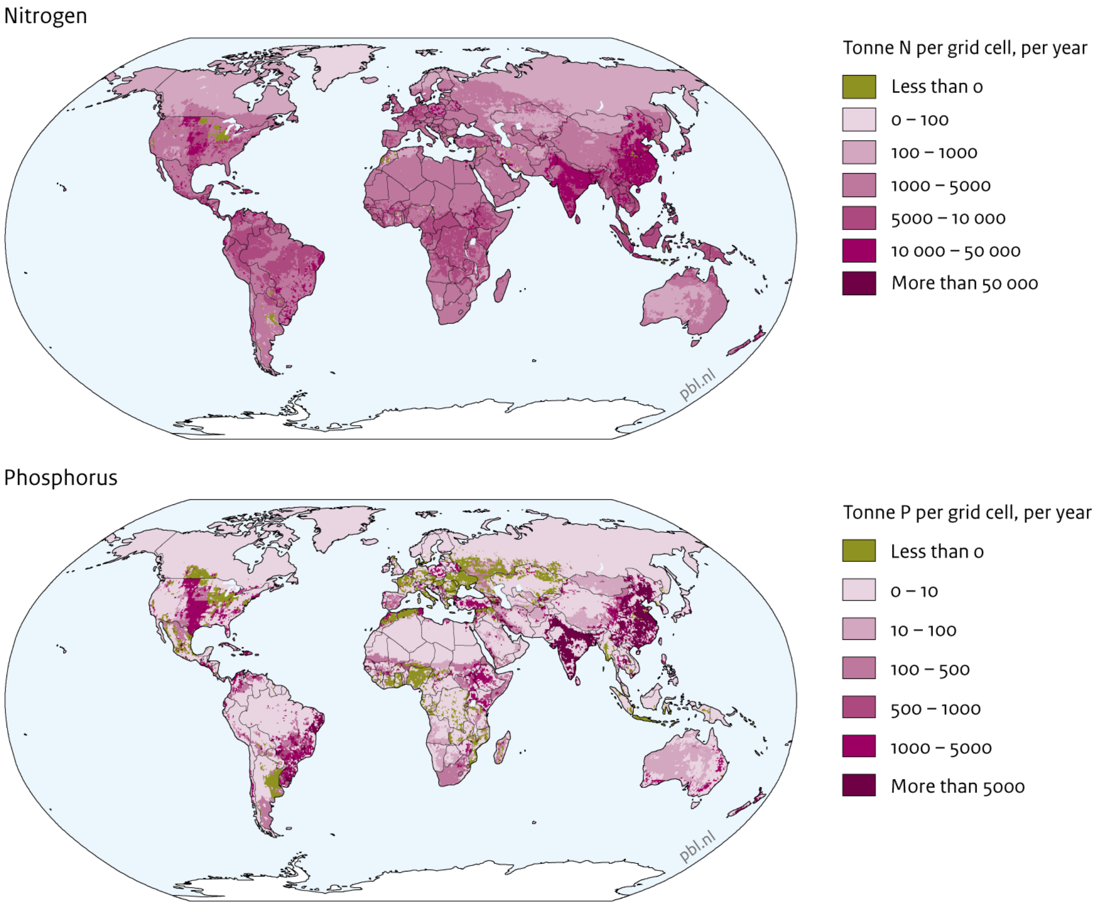
The availability of nutrients in the soil depends on the amount of nutrients it contains and the additional input it receives, such as fertiliser, manure, compost and atmospheric nitrogen deposition. Further nitrogen inputs may come from biological fixation, mainly by leguminous crops, such as beans and clover. Output consists of nutrients in the harvested parts of crops and losses, mainly in the form of nutrient run-off, leaching or wind erosion. However, losses can also occur in the form of emissions of ammonia, nitrous oxide (one of the major greenhouse gases) and inert nitrogen gas. Depending on the budget of inputs and outputs, soils can be stable in nutrient availability, enriched with nutrients (due to positive budgets) or depleted (due to negative budgets).

At present, almost all soils around the world have a positive nitrogen budget, with hotspots of surpluses in India, China and parts of Europe and the United States (Figure 1). For phosphorus, a more diverse pattern exists, with positive budget hotspots in parts of Europe, North and South

America and China, and large areas with negative budgets in Africa, North and South America, Central Asia and Europe (Figure 1). Residual soil budgets are the accumulation of nutrients in soils over multiple seasons. This applies mainly to P, as much of the residual N can be considered as an environmental burden: after the growing season, the soil will be denitrified, or surplus N will be leached or taken up by the next crop. In contrast, P is chemically absorbed by soil particles. P can be lost from soils in run-off in the form of dissolved reactive P and particulate P, and will leach into water systems only after long periods of excessive application.

Farmers in high-income countries and in China and India have built up a large reserve of residual soil P in cropland in recent decades. Crops can use this residual soil P stock; as a result, the use of mineral P fertiliser has been decreasing in many industrialised countries, in recent years. Soil P budgets are even negative in Europe to date. Large amounts of N surpluses are lost to the environment through emissions to air and water, and are transported in groundwater with long travel times (decades and longer). Thanks to increased efficiency in the use of N and the utilisation of accumulated residual soil P, continued increases in crop yields with decreasing losses to the environment can be achieved (Bouwman et al., 2017). However, with the memory effect of nutrient-rich aquifers in many landscapes, N concentrations in many rivers do not respond to the increased efficiency of fertiliser use. Consequently, water quality in Europe is being threatened by rapidly increasing N:P ratios (Bouwman et al., 2017). Farmers in developing countries can avoid this by learning from this legacy and by integrating management of N, P and other nutrients while accounting for residual soil P.

Nitrogen and phosphorus budget, 2010



Source: PBL

Figure 1. Nitrogen budget (top) and phosphorus budget (bottom) resulting from inputs (fertiliser, manure, biological fixation, and deposition) and removal (harvested crops and erosion) in kg per grid cell in 2010.

1.2 Methods and analysis

1.2.1 Model of household emissions

The emissions of nutrients from households were calculated with the Global Nutrient Model (Figure 2) (Beusen et al., 2016). Protein consumption and the use of laundry and dishwasher detergents are the primary sources of household emissions. After 1945, phosphorus became an important part of laundry and dishwasher detergents. In several countries, such as the United States and EU Member States, phosphorus-free detergents are now mandatory. Sewerage systems can result in a direct emission of the effluent to surface water or the effluent can be discharged to a wastewater treatment plant. In this model, emissions of nitrogen to surface water (E_{sw}^{N}) are calculated as:

$$E_{human}^{N} = Protein_{human} * f_N * (1 - f_{loss})$$

$$D_{sw}^{N} = Pop * E_{human}^{N} * (f_{SC} * (1 - NR^{N}) + f_{urban\ without\ SC} * f_{direct\ emission})$$

Where E_{human}^{N} is the emission of nutrients by households per capita, $Protein_{human}$ is the protein per capita that is bought by consumers, f_N is fraction nitrogen in protein and f_{loss} is the combination of household and retail loss before consumption. Thus, the term $(1 - f_{loss})$ is the correction for the protein that is actually consumed. D_{sw}^{N} is the discharge of nitrogen to surface water, *Pop* is the population of a country or a grid cell, f_{SC} is the fraction of households with sewerage connection, *NR* is nutrient removal by wastewater treatment plant, $f_{urban\ without\ SC}$ is the urban population without sewerage connection and $f_{direct\ emission}$ is the part of the nutrients that directly enters surface water when no sewerage system is used. The urban population not connected to sewerage systems is assumed to discharge their waste directly into streets or canals near their homes, thus accounting for nutrient removal by denitrification of N; the urine part of human waste is assumed to be discharged to surface water. In rural areas, non-sewerage emissions are assumed not to account for discharges to surface water but to result in local pollution. Removal of nutrients by wastewater treatment plants is differentiated into primary treatment with 10% nutrient removal, secondary treatment with 35% N and 45% P removal and tertiary treatment with 80% N and 90% P removal. Phosphorus discharges were calculated the same way in which the phosphorus content of laundry and dishwasher detergents was also included in the total discharges.

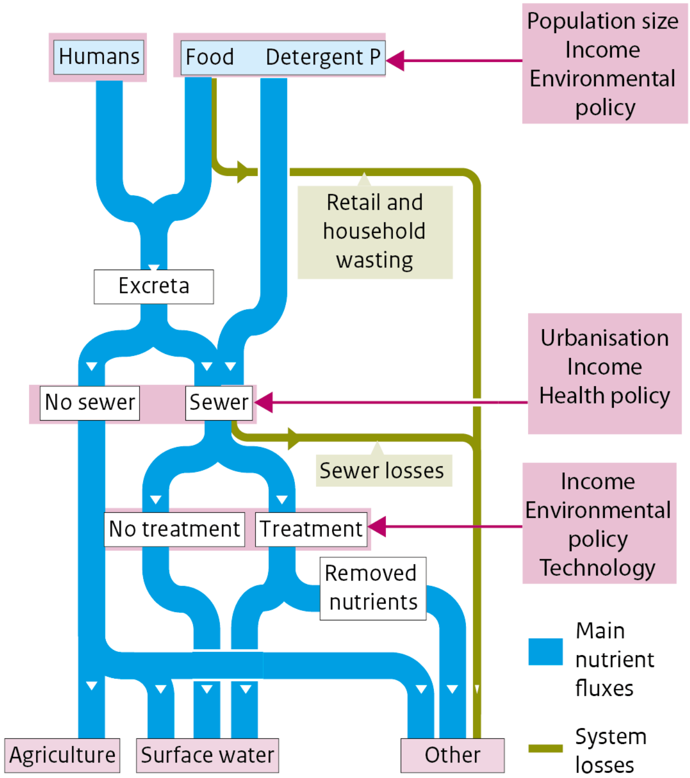


Figure 2. Population size, urbanisation and income affect nutrient emissions to surface water, with increases in income being associated with increases in protein consumption and the use of laundry and dishwasher detergents. The construction of sewerage systems and wastewater treatment plants is associated with an increase in income, urbanisation and environmental policy. Population growth is a main driver.

Input for Shared Socioeconomic Pathways (SSP) Scenarios

So far, human consumption, the primary source of human waste, has increased with increasing prosperity. For our calculations, we based human consumption on protein consumption data from FAO (2017) and Morée (2013). Thus, protein consumption was related to GDP (Figure 3a) and is assumed to increase, on average, from 85 to 103 g/cap/day, in the 2010–2050 period. Data on sewerage connection were derived from a previous version of the model (Morée et al., 2013; Van Drecht et al., 2009) and updated with information retrieved from the Joint Monitoring Program (JMP) (WHO and Unicef, 2015) and OECD (OECD, 2016; WHO and Unicef, 2015). In several cases, additional information on sewerage connection was derived from scientific literature (Miller and Parker, 2013; Reder, 2017).

Information on wastewater treatment was also obtained from Morée et al. (2013) and Van Drecht et al. (2009). Data on OECD countries were updated with recent data (OECD, 2016). Data on China were updated with recent information from the Chinese Government (NDRC, 2016). Data of UN on total wastewater treatment were compared with the sum of primary, secondary and tertiary treatment (UN, 2017). Different types of wastewater treatment were aggregated to a percentage nutrient removal. Both sewerage connection and percentage nutrient removal were related to GDP (Figures 3b and c). For the future, a quaternary treatment level was added to include potential future technological innovations on wastewater treatment that may allow for the removal of 95% of the nutrients. Scenarios for protein consumption, household connection to sewerage systems, and wastewater treatment were based on projected GDP growth and urbanisation of each country for SSP1, SSP2 and SSP3. Sewerage connection and nutrient removal through wastewater treatment will increase with prosperity, and wastewater treatment levels are increased as GDP grows (Figure 3d).

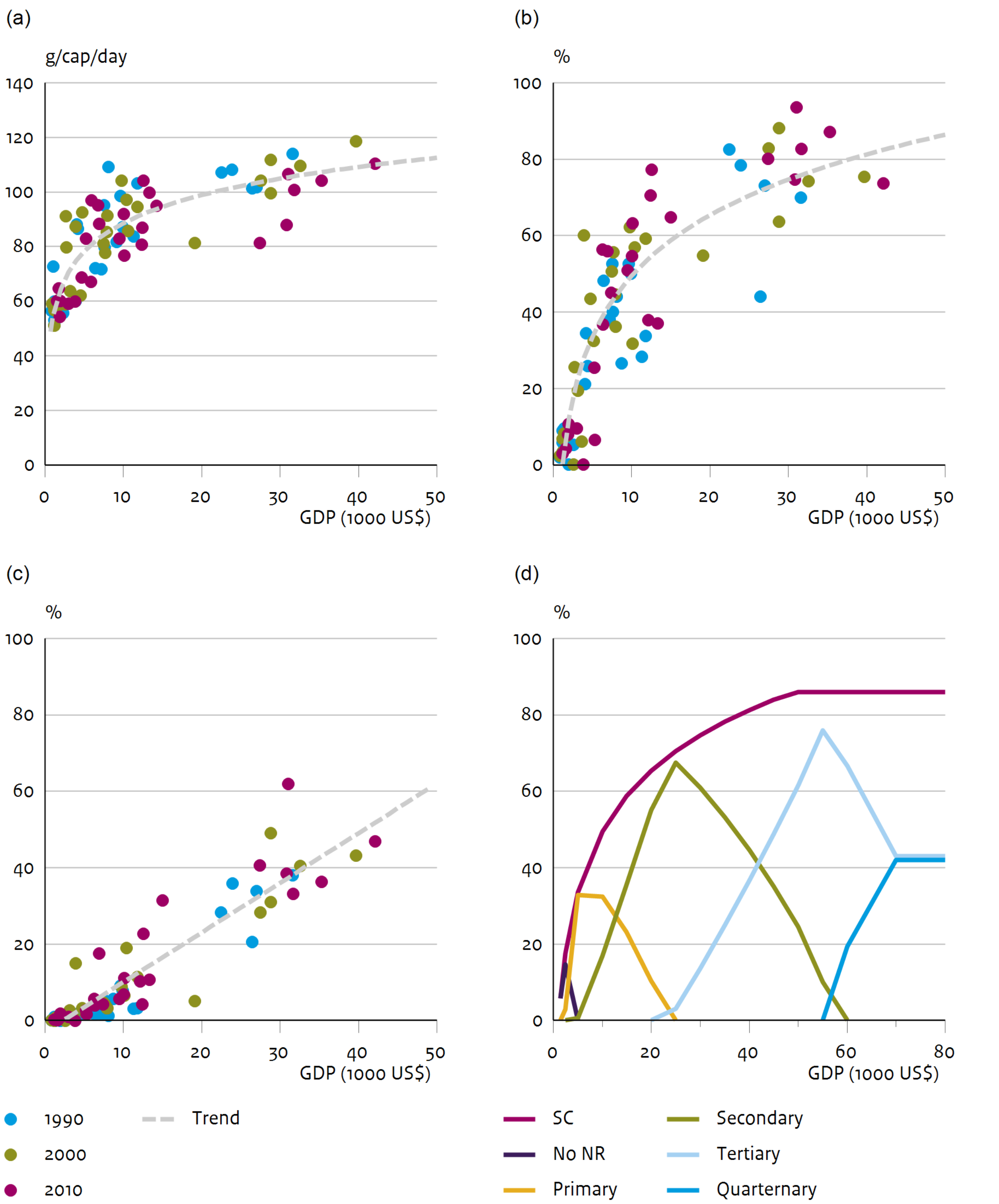


Figure 3. Global relationships between GDP and protein consumption (a), percentage of households connected to sewerage (b), percentage of nutrient removal related to GDP (c) for IMAGE regions, for three years, and (d) an example of improvements in sewerage connection and wastewater treatment as GDP levels grow.

Rich–poor gap on sanitation within cities

The level of improved sanitation is affected by the gap between the rich and the poor, both between countries and within cities (GFWC, p. 41). These differences are striking for the containment, transport and treatment of human waste (Figure 4). Two examples are Lima, the capital of Peru, with a population of just under 10 million, and Dhaka, the capital of Bangladesh, with a population of 6.6 million. Nearly 50% of the residents in these cities live in slum settlements (World Bank, 2016). In the city of Lima, 92% of waste water is discharged into a sewerage system and 4% into septic tanks. Due to sewer leakages, 18% of the sewage does not reach wastewater treatment plants, and 25% is discharged directly into the sea. Of the remaining part, 52% of the waste is treated. In the slums of Lima, covering 50% of the city, most people use pits for their waste and these pits are abandoned when full. Of the slum area, only 1% of the waste is transported to a wastewater treatment plant and 99% is discharged locally into drains, without being treated, or stored in abandoned pit latrines. The percentage of unimproved sanitation in cities is 5% and in slums it is 99%.

In Dhaka (Bangladesh), nearly all city households have a flush or a pour-flush toilet, while half of the slum population has a pour-flush toilet and the rest a pit latrine or a hanging toilet. A quarter of the city's household waste is discharged via a sewerage system and three-quarters is directly or indirectly discharged into local drains. In the slums, all waste water is discharged into local drains or stored in pit latrines.

These examples show that, in the city, human waste is transported away from the population, with less risk to human health, and mostly discharged to surface waters without being treated, thus increasing ecological risks. In the slums, there are major threats to local health as human waste is deposited near households.

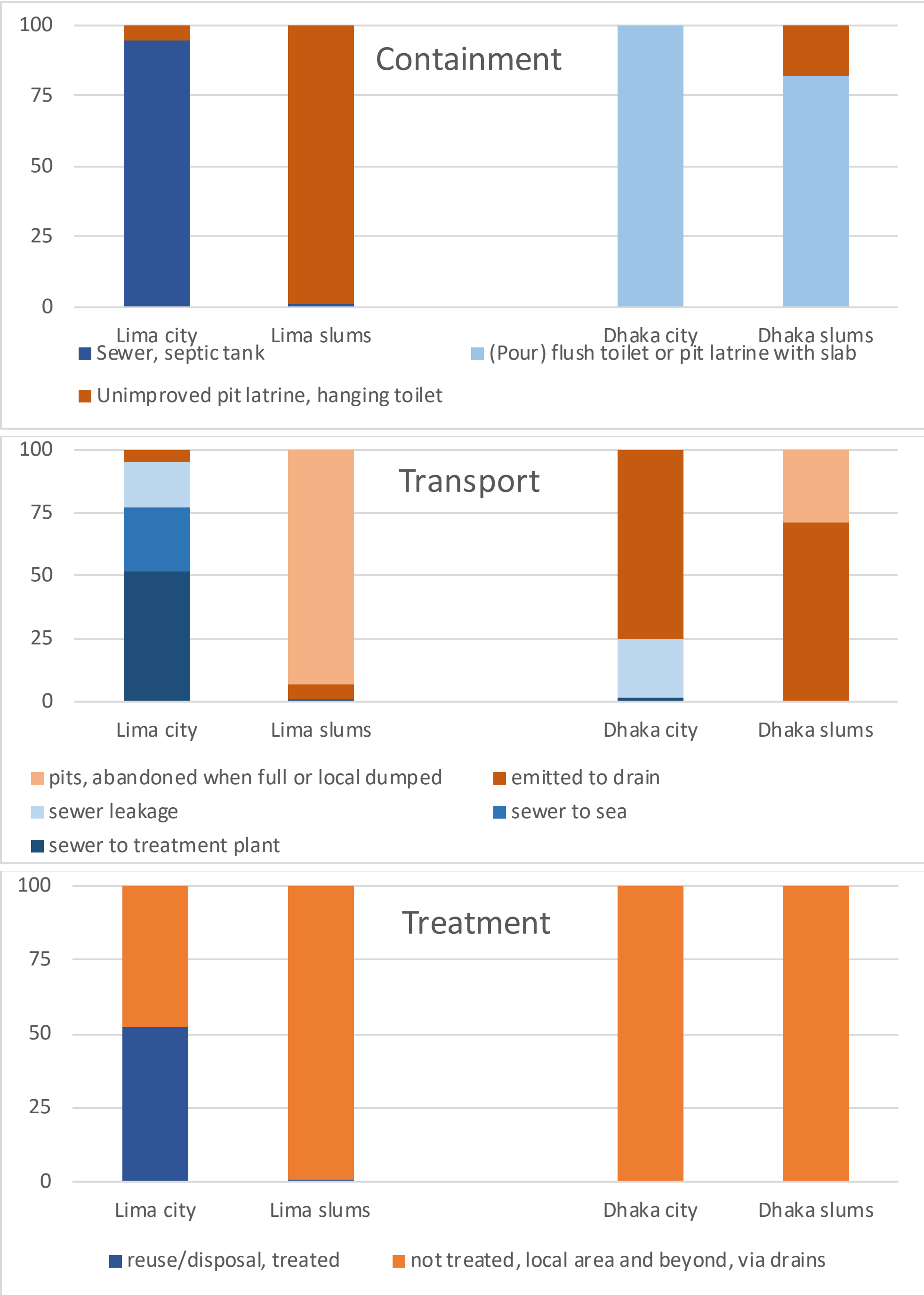


Figure 4. Faecal waste containment, transport and treatment for the city and the slums of Lima and Dhaka (World Bank, 2016). Blue bars represent improved or sustainable sanitation; orange bars represent unimproved or not sustainable sanitation.

1.2.2 Model of agricultural emissions

In this study, emissions from agriculture are based on the agricultural scenarios included in the IMAGE model. The soil budget approach (Bouwman et al., 2009; Bouwman et al., 2013) considers all N and P inputs and outputs for IMAGE grid cells. N input terms in the budgets include application of synthetic N fertiliser (N_{fert}) and animal manure (N_{man}), biological N fixation (N_{fix}) and atmospheric N deposition (N_{dep}). Output terms include N withdrawal from the field through crop harvesting, hay and grass cutting and grass consumed by grazing animals (N_{withdr}).

The soil N budget (Nbudget) was calculated as follows:

$N_{budget} = N_{fert} + N_{man} + N_{fix} + N_{dep} - N_{withdr}$

The same approach was used for P, with input terms being animal manure and fertiliser. The soil nutrient budget does not include nutrient accumulation in soil organic matter for a positive budget (surplus), or nutrient depletion due to soil organic matter decomposition and mineralisation. With no accumulation, a surplus represents a potential loss to the environment. For N, this includes NH_3 volatilisation, denitrification, surface run-off and leaching. For P, this is surface run-off.

For spatial allocation of the nutrient input to IMAGE grid cells, the crop groups in IMAGE (temperate cereals, rice, maize, tropical cereals, pulses, roots and tubers, oil crops, other crops, energy crops) and grass were aggregated into five broad groups. These groups are grass, wetland rice, leguminous crops, other upland crops and energy crops for both mixed and pastoral production systems.

Fertiliser use was based on nutrient use efficiency, representing crop production in kilograms of dry matter per kilogram of fertiliser N (NUE) and P (PUE). NUE and PUE vary between countries because of differences in crop mix, attainable yield potential, soil quality, amount and form of N and P application and management. In constructing scenarios on fertiliser use, data on the 1970–2005 period serve as a guide to distinguish countries with an input exceeding crop uptake (positive budget or surplus) from countries with a deficit. Generally, farmers in countries with a surplus are assumed to be increasingly efficient in fertiliser use (increasing NUE and PUE). In countries with nutrient deficits, an increase in crop yields is only possible with an increase in the nutrient input. Initially, this will lead to decreasing NUE and PUE, showing a decrease in soil nutrient depletion due to increased fertiliser use.

Total manure production was computed from animal stocks, and N and P excretion rates. IMAGE uses constant N and P excretion rates per head for dairy and non-dairy cattle, buffaloes, sheep and goats, pigs, poultry, horses, asses, mules and camels. Constant excretion rates imply that the N and P excretion per unit of product decreases with increased milk and meat production per animal.

N and P in the manure for each animal category were spatially allocated to mixed and pastoral systems. In each country and system, the manure is distributed over three management systems: grazing, storage in animal housing and storage systems, and manure used outside the agricultural system for fuel or other purposes. The quantity of manure assigned to grazing is based on the proportion of grass in feed rations.

Stored animal manure available for cropland and grassland application includes all stored and collected manure, excluding ammonia volatilisation from animal houses and storage systems. In general, IMAGE assumes that 50% of available animal manure from storage systems is applied to arable land and the rest to grassland in industrialised countries. In most developing countries, 95% of the available manure is spread on croplands and 5% on grassland, thus accounting for the lower economic importance of grass compared to crops in these countries. In the European Union, maximum manure application rates are 170 to 250 kg N per ha, reflecting current regulations.

Data on biological N_2 fixation by leguminous crops (pulses and soya beans) were obtained from the N in the harvested product (see nutrient withdrawal). Thus any change in the rate of biological N_2 fixation by legumes is the result of yield changes for pulses and soybeans. In addition to leguminous crops, IMAGE uses an annual rate of biological N_2 fixation of 5 kg N per ha for non-leguminous crops and grass, and 25 kg N per ha for wetland rice. N fixation rates in natural ecosystems were based on the low estimates for areal coverage by legumes (Cleveland et al., 1999) as described by Bouwman et al. (2013).

Atmospheric deposition rates for historical and future years were calculated by scaling an N deposition map for 2000 (obtained from atmospheric chemistry transport models), using emission inventories for the historical period and projections of N gas emissions in the scenario considered. IMAGE does not include atmospheric P deposition.

Withdrawal of N and P in harvested products was calculated from regional crop production in IMAGE, and the N and P content for each crop, which is aggregated to the broad crop categories (wetland rice, leguminous crops, upland crops and energy crops). IMAGE also accounts for uptake by fodder crops. N withdrawal through grass consumption and harvest was assumed to amount to 60% of all N input (manure, fertiliser, deposition, N fixation), excluding NH_3 volatilisation. P withdrawal through grazing or grass cutting was calculated as a proportion of 87.5% of fertiliser and manure P input. The rest is assumed to be lost through surface run-off. In calculating spatially explicit nutrient withdrawal, a procedure was used to scale down regional crop production data from IMAGE to country estimates for nutrient withdrawal based on distributions in 2005.

Nutrient losses from the plant-soil system to the soil-hydrology system were calculated from the soil nutrient budgets (Bouwman et al., 2013). For N, the budget is corrected for ammonia volatilisation from grazing animals and from fertiliser and manure spreading (see Section 5.2, Emissions). P not taken up by plants is generally bound to soil particles, with the only loss pathway being surface run-off. N is more mobile and is transported via surface run-off and through soil, groundwater and riparian zones to surface water.

Denitrification in the soil was calculated as a proportion of the soil N budget surplus based on the effect of temperature and residence time of water and nitrate in the root zone, and the effects of soil texture, soil drainage and soil organic carbon content. In a soil budget deficit, IMAGE assumes that denitrification does not occur. Leaching is the complement of the soil N budget.

Model to calculate nutrient load to coastal seas

Two groundwater subsystems were distinguished. One is the shallow groundwater system, representing interflow and surface run-off for the upper 5 m of the saturated zone, with short travel times for the water to enter local surface water at short distances or to infiltrate the deep groundwater system. The other is the deep system with a thickness of 50 m, with generally long travel times, draining to larger streams and rivers. Deep groundwater was assumed to be absent in areas of non-permeable, consolidated rock or in the presence of surface water.

Denitrification during groundwater transport in the deep system is based on the travel time and the half-life of nitrate. The half-life depends on the lithological class (one year for schists and shales containing pyrite, two years for alluvial material and five years for all other lithological classes). Flows of water and nitrate from shallow groundwater to riparian zones were assumed to be absent in areas with surface water bodies, where the flow was assumed to bypass riparian zones flowing directly to streams or rivers. Denitrification in riparian areas was calculated similar to that in soils, but with two differences: a biologically active layer of 0.3 m thickness was assumed instead of 1 m for other soils, and the approach includes the effect of pH on denitrification.

The water that enters streams and rivers through surface run-off and discharges from groundwater and riparian zones is routed through stream and river channels and passes through lakes, wetlands and reservoirs. The nutrient retention in each of these systems was calculated on the basis of the nutrient spiralling ecological concept, which is based on residence time and temperature as described in Beusen et al. (2016).

1.3 Results

1.3.1 Household emissions

The number of sewerage connections has increased in many countries in the 1970–2010 period, except in Africa and Southeast Asia (Figures 5 and 6). In the future, most countries will probably invest in sewerage systems: between two and four billion people will become connected to a sewerage system between 2010 and 2050. The number of people without sewerage connection decreases under SSP1 and SSP2, and increases under SSP3 (Table 2). The number of people connected to wastewater treatment plants increases in all scenarios, but, in Sub-Saharan Africa, wastewater treatment is mostly limited to primary treatment. According to the scenarios, treatment in the other regions will be extended with secondary treatment or higher (Figure 6). In the developed countries, treatment will be extended with tertiary or advanced quaternary treatment. The differences between SSP1, SSP2 and SSP3 show that SSP1 has the lowest number of inhabitants without sewerage connection and SSP3 had the highest number; also, the number of inhabitants with secondary or higher treatment is highest under SSP1 and lowest under SSP3.

A part of the emissions from household connections results from the use of detergents for laundry and dishwashers. Since 1940, the use of laundry and, later, dishwasher detergents with a high phosphorus content became important and resulted in major eutrophication in lakes in the United States and other countries. Later, environmental policy reduced the use of phosphorus, first in laundry detergents and more recently in dishwasher detergents (EC, 2011; EU, 2012).

The use of washing machines and dishwashers increases with increasing prosperity. Without environmental policy, this would lead to an increasing source of phosphorus discharges, from 0.09 kg cap^{-1} $year^{-1}$ in 2010 to 0.2 kg cap^{-1} $year^{-1}$ by 2050. SSP2 assumes that, in countries with a GDP above USD 40000/year in 2050, detergents with a low P content will be used, resulting in a P content of 0.17 kg cap^{-1} $year^{-1}$. Discharges of N and P increased between 1970 and 2010 (Figure 8) in all regions, except for the developed countries due to environmental policy. For example, policy in the EU to reduce nutrient loads resulted in an upgrade to tertiary wastewater treatment in most countries (EEC, 1991). In the next 40 years, the global emissions are projected to increase by 70% for nitrogen and 25%–75% for phosphorus (the solid lines in figure 8 represent SSP1, SSP2 and SSP3).

According to the SSP scenarios, N and P loads will be reduced in 2050 in the developed countries. In Latin America, northern Africa, the Middle East and Russia, nutrient loads increase under SSP2 and SSP3, and decrease under SSP1. In South Asia and Asia Pacific, the loads slightly increase or double under these scenarios, while an extreme increase is projected for Sub-Saharan Africa.

Table 2. Global population with (SC) and without (no SC) sewerage connection, global population per type of wastewater treatment (in millions), and global emissions of N and P. All SSP scenarios and two variants on SSP2 refer to 2050 (GFWC, p. 40).

	Sewerage (million people)		Wastewater treatment level (million people)				Discharge (billion kg)	
	no SC	SC	Primary	Secondary	Tertiary	Quaternary	N	P
1970	2,915	779	183	144	5	0	5.3	0.8
2010	4,434	2,456	860	567	508	0	10.4	1.5
SSP1	2,159	6,318	709	2,774	1,975	835	15.7	1.7
SSP2	3,579	5,602	1,043	2,780	1,413	303	16.9	2.4
SSP3	5,375	4,588	1,305	2,086	1,035	0	15.8	2.4
SSP2 secondary	3,578	5,603	0	3,823	1,413	303	15.4	1.4
SSP2 tertiary	3,578	5,603	0	0	5,237	303	6.3	0.4

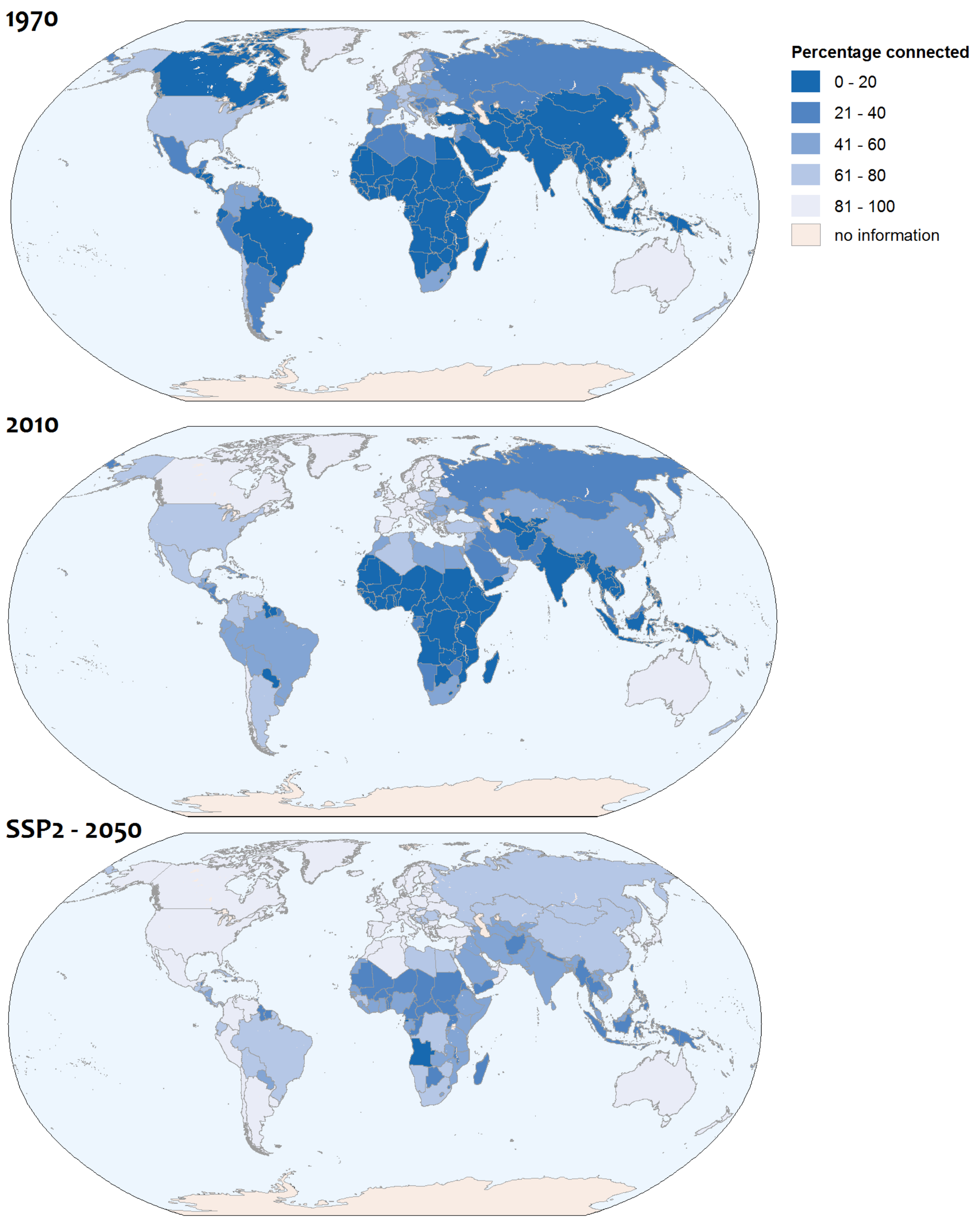


Figure 5. Sewerage connection of households, data for 1970 and 2010 based on global databases, and projection for 2050 under the SSP2 scenario based on IMAGE calculations (OECD, 2016; Van Drecht et al., 2009; WHO and Unicef, 2015)

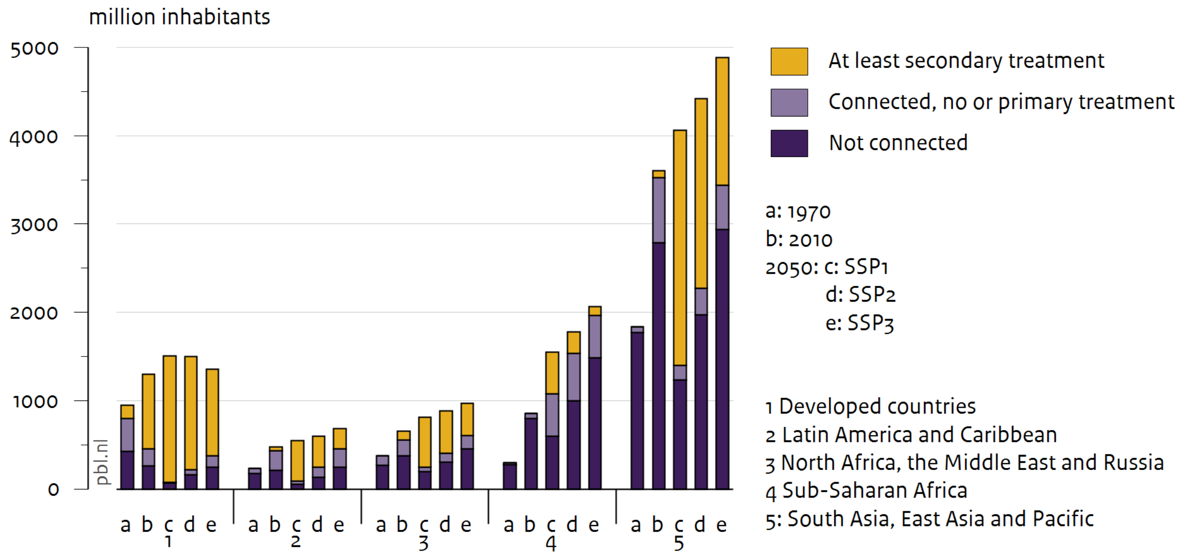


Figure 6. The number of people connected to a sewerage system with a distinction between people being connected to at least secondary wastewater treatment and others, in five global regions in 1970 and 2010, and projections for 2050 under three SSP scenarios for socio-economic development.

On a global scale, total emission levels from agriculture are higher than from households, but the latter are concentrated in relatively small, urbanised areas (Figure 7). For SSP2, two variants were analysed: under the first, the effluent from all sewerage systems receives at least secondary treatment; under the second, all effluent receives tertiary or higher treatment (the broken lines in Figure 8). Both variants also have P-free detergents. The switch to P-free detergents and the upgrade to secondary and tertiary treatment gradually changes, between 2010 and 2050. With tertiary treatment at all treatment plants, nitrogen discharges are reduced to 60%, compared to 2010 discharge levels. Phosphorus is reduced even further, since the nutrient removal under tertiary treatment includes 90% phosphorus removal.

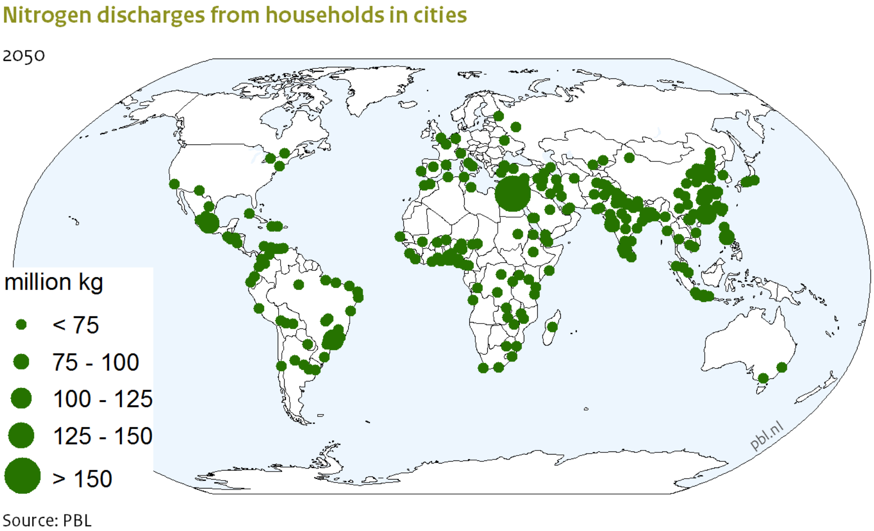


Figure 7. Nitrogen discharges to surface water from households, from cities with more than 500,000 inhabitants, which were buffered to ¼ degree and aggregated when close to each other.

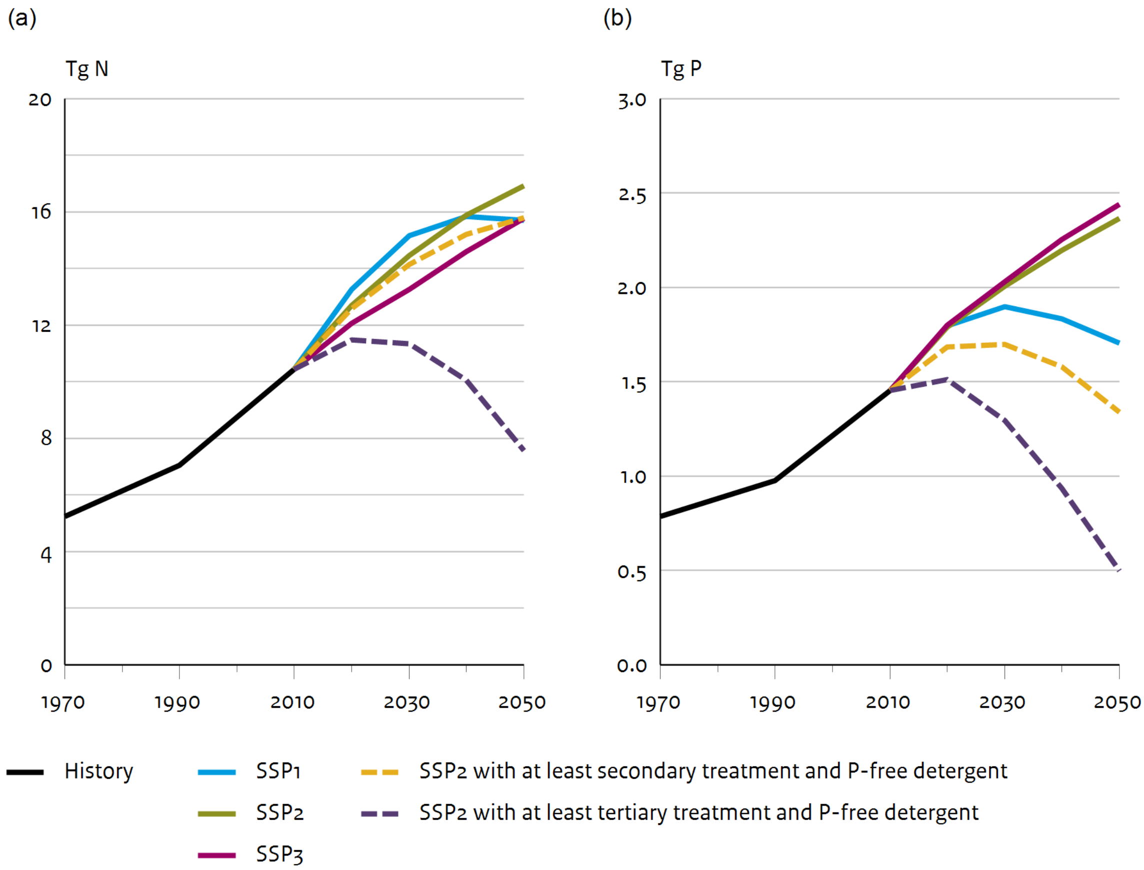


Figure 8. Projections of global nitrogen (a) and phosphorus (b) up to 2050, according to three scenarios. In addition to scenario SSP2, two variants are presented (broken lines) in which all sewerage systems have secondary or tertiary treatment and detergents are phosphorus-free (GFWC, pp. 42–43).

1.3.2 Agriculture emissions

Under the SSP2 scenario, nitrogen and phosphorus fertiliser use increase along with an increase in food production (Figure 9), especially in regions where use is currently still low. On a global scale, this leads to a massive accumulation of fertiliser in soils and groundwater up to 2050.

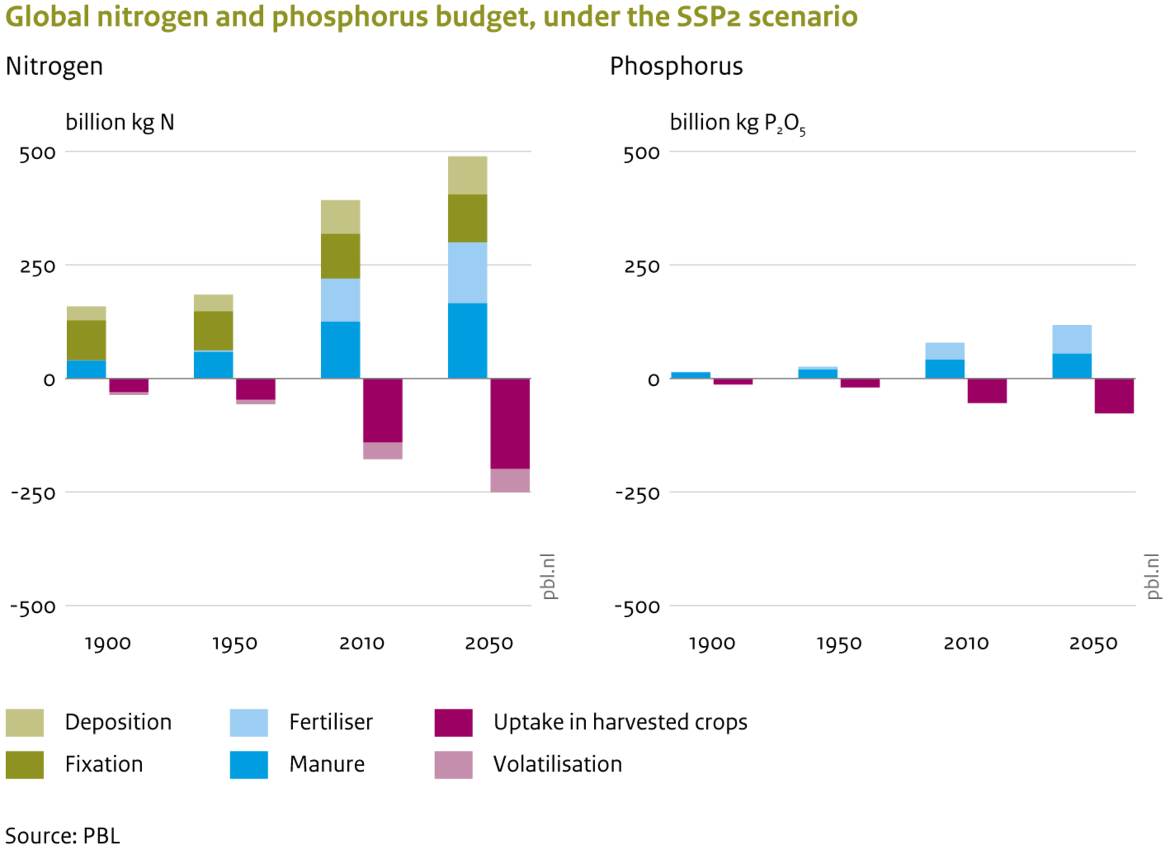


Figure 9. Changes in global nitrogen (left) and phosphorus budgets (right) in 1900, 1950, 2010 and under the SSP2 scenario up to 2050. The graphs show a substantial increase in the total quantities of these nutrients on the global scale.

While overall phosphorus and nitrogen flows have increased over time, there are also large areas that had a negative phosphorus budget over the 1970–2010 period (Figure 10). Large areas with significant negative phosphorus budgets are found in Africa, North and South America, the Mediterranean area and China. Under the SSP2 scenario, the soil depletion in these areas is projected to continue. In areas with a negative budget for phosphorus, the risk of decreasing crop production depends on the stock of available nutrients in the soil. As the knowledge about these nutrient stocks is relatively low, the potential future impact of changes in agricultural management on crop yields cannot be assessed.

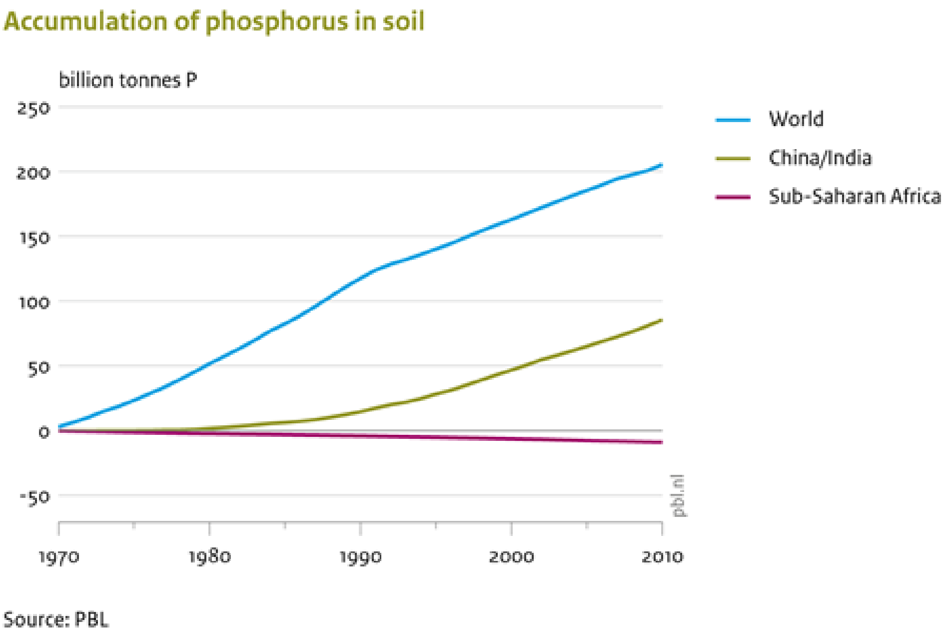


Figure 10. Total accumulation of phosphorus in the soil, globally and for the regions China and India and Sub-Saharan Africa.

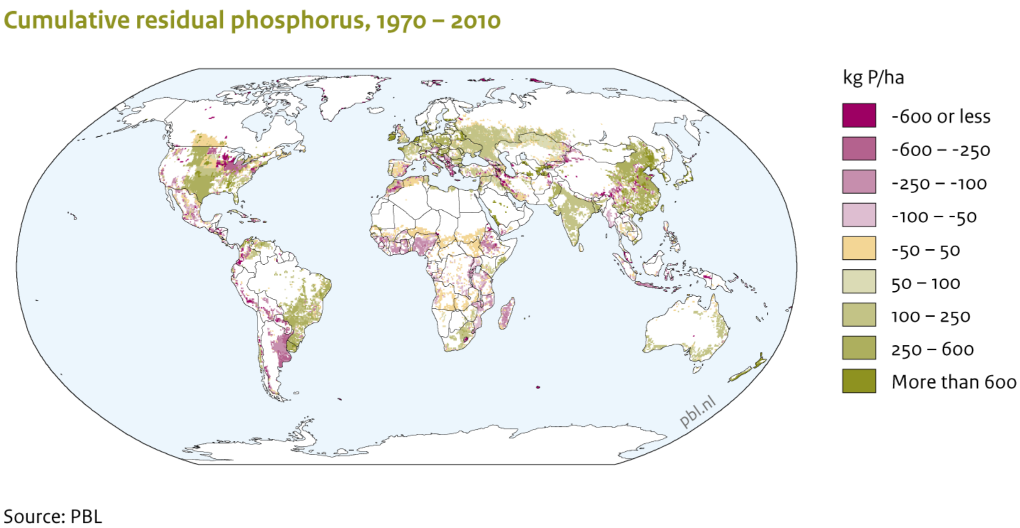


Figure 11. Large areas with significant phosphorus depletion over the period 1970–2010 are found in Africa, North and South America, the Mediterranean area and Asia (purple). Significant phosphorus accumulation occurs in parts of Europe, North and South America and China (green).

Positive nitrogen budgets lead to enriched soils and increased groundwater pollution, as well as nutrient loading of streams, rivers, lakes, reservoirs and coastal seas. Phosphorus is lost from soil-crop systems through surface run-off, and the accumulation of P in soils may lead to high P content in that run-off (Beusen et al., 2016). Certain phenomena, such as harmful algal blooms, oxygen depletion, hypoxia and fish kill, are well-known effects from increased nitrogen or phosphorus application (Diaz and Rosenberg, 2008).

Both N and P emissions will increase, globally, by 13% for N and 19% for P, up to 2050. Especially in China, nitrogen emissions are projected to decrease due to a reduction in fertiliser use. In Africa, the Middle East, Central and South America and South Asia, N emissions will increase by 70% to 100% and P emissions by 20% to 100%. In Russia and Central Asia, the China region and Southeast Asia, both N and P emissions will decrease by 5% to 25% (Table 3).
Especially in parts of Africa, North and South America, the Mediterranean area and China, negative phosphorous budgets occur that may carry the future risk of nutrient depletion. Information on the nutrient stocks is required to assess if and when in time this may hamper food production.

Table 3. N (top) and P (bottom) discharges from households and agriculture to surface water, under SSP2 for 2010 and 2050 (GFWC, pp. 42–43).

Nitrogen (10^9 kg)	2010			2050		
	Agricul-ture	House-holds	Total	Agricul-ture	House-holds	Total
Canada	0.62	0.15	0.77	0.62	0.12	0.73
United States, Mexico	2.62	0.94	3.56	2.71	0.99	3.70
Europe	2.18	1.44	3.61	2.21	1.36	3.57
South and Central America	3.14	1.25	4.39	5.49	1.85	7.34
Northern Africa, Central Asia	1.23	0.97	2.20	2.14	2.51	4.64
Russia	1.66	0.47	2.13	1.46	0.59	2.05
Sub-Saharan Africa	1.21	0.48	1.69	2.25	2.59	4.84
South and East Asia	19.27	3.63	22.90	19.29	8.67	27.95
Japan, Oceania	0.68	0.33	1.01	0.82	0.23	1.06
	32.60	9.66	42.26	36.98	18.90	55.89

Phosphorus (10^9 kg)	2010			2050		
	Agricul-ture	House-holds	Total	Agricul-ture	House-holds	Total
Canada	0.08	0.02	0.10	0.07	0.01	0.08
United States, Mexico	0.38	0.11	0.50	0.49	0.12	0.61
Europe	0.53	0.17	0.70	0.61	0.15	0.76
South and Central America	0.66	0.19	0.84	0.88	0.27	1.15
Northern Africa, Central Asia	0.70	0.13	0.83	0.80	0.35	1.15
Russia	0.43	0.07	0.49	0.38	0.08	0.45
Sub-Saharan Africa	0.35	0.07	0.42	0.54	0.36	0.90
South and East Asia	2.11	0.48	2.59	2.49	1.20	3.69
Japan, Oceania	0.20	0.04	0.24	0.24	0.03	0.26
	5.45	1.27	6.71	6.51	2.55	9.06

1.3.3 Nutrient load to oceans

Not all of the nutrients discharged from households and agriculture to surface water are transported to the sea. Both nitrogen and phosphorus will partly be lost, along the way, due to uptake by plants and algae, while some of the nitrogen is also lost due to denitrification, and some of the phosphorus

due to sedimentation. Especially in lakes and reservoirs, sedimentation of suspended matter and dead algae is important in reducing the phosphorus concentration in the water.
Oceans and coastal seas with high nutrient loads are the Yellow Sea with the Huang He, the North Brazil Shelf with the Amazon, the Bay of Bengal with the Ganges and Brahmaputra, the South China Sea with the Jangtsekiang, the Arabian Sea with the Indus and the Mediterranean Sea (Table 4, Figure 12). In most coastal seas, nutrient loads are projected to increase between 2010 and 2050, by up to more than 50% in the Arabian Sea, the Somali Coastal Current, the Guinea Current, the Red Sea, the Bay of Bengal and the Gulf of Thailand.

Already, many coastal seas suffer from high nutrient loads, affecting ecosystems through eutrophication with high algae growth. The decay of algal biomass accompanied with decreased oxygen concentrations (hypoxia) and the production of toxins by cyanobacteria both result in fish kills (Diaz and Rosenberg, 2008). Globally, the abundance of cyanobacterial blooms is increasing (Huisman et al., 2018). For example, in recent years, increasing occurrences of algal blooms have been reported for the East China Sea (Li et al., 2009; Zhang et al., 2013), the Philippines (David et al., 2009) and Malaysia (Anton et al., 2008).

This high nutrient load, which started already several decades ago and will continue in the next decades, can result in a major eutrophication problem in coastal seas.

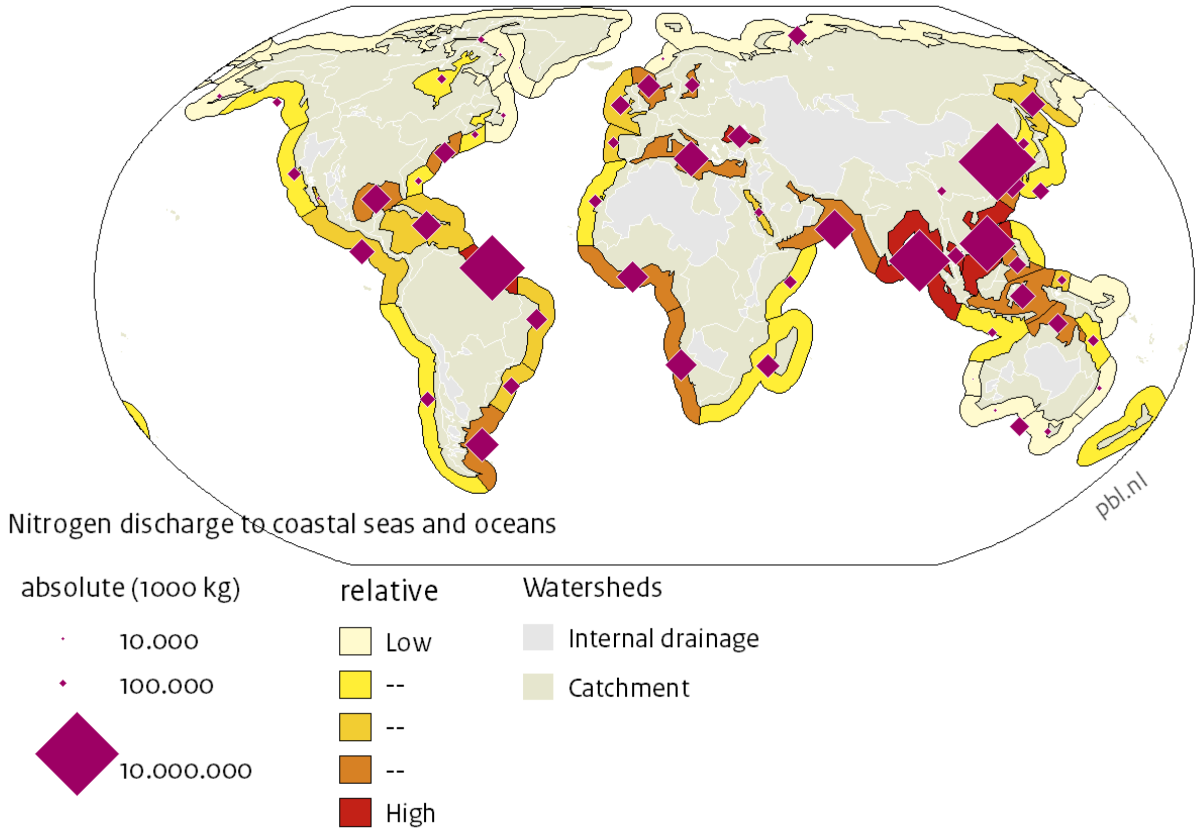


Figure 12. Discharges of Nitrogen into coastal seas and oceans. Internal drainage areas do not discharge into oceans (GFWC, p. 60).

1.4 Conclusions

In this report, the status and potential developments of waterborne diseases, sanitation and emissions of nutrients are presented. Waterborne diseases and sanitation are closely related as unimproved sanitation is a major cause of mortality due to diarrhoea and cholera. Sanitation and wastewater treatment have a major impact on the nutrient loads being discharged to surface water and the eutrophication of fresh waters and coastal seas.

Globally, 780,000 people die yearly due to waterborne diseases, with 685,000 deaths due to diarrhoea and 95,000 deaths due to cholera. Mortality due to waterborne diseases is much higher than due to other water-related causes; each year, 6,000 deaths are caused by flooding and 1,100 by drought. Although flooding and drought receive much more public attention because of the local impact, waterborne diseases take a much higher toll on human health.

To improve health and reduce mortality, unimproved sanitation has to be changed to improved sanitation. Improved sanitation are septic tanks, improved pit latrines and flush toilets connected to sewerage systems. Nowadays, one third of the global population does have a household connection to a sewerage system. It is projected that, in 2050, about two thirds of the global population will be connected to a sewerage system. Although this represents a major improvement in sanitation, a part of the population will still be without improved sanitation.

With the increase in sewerage connection, wastewater treatment often lags behind. Without wastewater treatment, human waste is discharged directly to surface water. The direct discharge of human waste results in high organic loads. The first step is to add primary treatment, which will reduce organic loads but hardly affects nutrient loads. Secondary, tertiary or more advanced quaternary treatment also reduces nutrient loads.

The other major source of nutrient loads is from fertiliser use and manure production in agriculture. This results in a higher, but more diffuse loading of nutrients to surface water, compared to those from households. For the future, nutrient loads from agriculture are projected to stabilise or decrease, on a global scale, but may still increase locally. Therefore, household emissions will become relatively more important.

The Sustainable Development Goals define targets for improved sanitation, wastewater treatment and water quality. The SDG target for improved sanitation for all by 2030 will not be achieved, especially not in Sub-Saharan Africa. The SDG target for wastewater treatment is aimed to halve the amount of untreated waste water, with primary wastewater treatment at a sufficient level. Therefore, nutrient discharges to surface water will increase, especially after SDG targets are achieved.

Table 4. Discharges of nitrogen (N) and phosphorus (P) into seas and oceans, in million kg per year.

		N		P	
seacd	seanm	2010	2050	2010	2050
1	East Bering Sea	35	34	7	7
2	Gulf of Alaska	174	113	45	30
3	California Current	330	259	48	38
4	Gulf of California	15	21	2	3
5	Gulf of Mexico	1,278	1225	85	98
6	Southeast US Continental Shelf	50	62	3	3
7	Northeast US Continental Shelf	545	612	32	31
8	Scotian Shelf	107	80	6	4
9	Newfoundland–Labrador Shelf	48	32	3	2
10	Insular Pacific–Hawaiian	52	45	22	20
11	Pacific Central–American Coastal	559	1,003	127	213
12	Caribbean Sea	807	1,197	133	185
13	Humboldt Current	359	389	62	57
14	Patagonian Shelf	1,130	1,683	121	150
15	South Brazil Shelf	335	398	44	47
16	East Brazil Shelf	521	708	66	78
17	North Brazil Shelf	5,860	6,263	444	468
18	West Greenland Shelf	6	6	2	2
21	Norwegian Sea	19	19	2	2
22	North Sea	954	783	73	57
23	Baltic Sea	348	321	21	17
24	Celtic–Biscay Shelf	590	506	57	49
25	Iberian Coastal	192	202	23	25
26	Mediterranean Sea	1,362	1,849	250	332
27	Canary Current	143	238	24	33
28	Guinea Current	768	1,394	86	167
29	Benguela Current	1,075	1,357	56	83
30	Agulhas Current	486	807	63	105
31	Somali Coastal Current	120	254	14	32
32	Arabian Sea	797	2,125	112	251
33	Red Sea	52	118	10	19
34	Bay of Bengal	3,355	5,501	318	520
35	Gulf of Thailand	281	438	20	30
36	South China Sea	4,436	4,389	308	364
37	Sulu–Celebes Sea	257	425	28	48
38	Indonesian Sea	940	987	145	147
39	North Australian Shelf	518	563	56	61
40	Northeast Australian Shelf	167	186	34	39
41	East–Central Australian Shelf	30	31	5	5

42	Southeast Australian Shelf	61	74	8	10
43	Southwest Australian Shelf	18	23	3	3
44	West–Central Australian Shelf	5	8	1	1
45	Northwest Australian Shelf	112	130	18	20
46	New Zealand Shelf	336	508	69	87
47	East China Sea	1,050	861	83	73
48	Yellow Sea	9,562	8,632	668	666
49	Kuroshio Current	479	410	55	53
50	Sea of Japan	254	210	34	28
51	Oyashio Current	131	128	25	24
52	Sea of Okhotsk	1,004	933	53	59
53	West Bering Sea	151	154	58	56
60	Faroe Plateau	1	1	0	0
62	Black Sea	834	806	109	100
63	Hudson Bay	135	130	7	7
66	Baffin Bay Davis Strait	15	15	2	2
91	America Arctic	70	70	11	11
92	Eurasia Arctic	704	706	92	89
100	Endoreic	0	0	0	0
	Total	44,021	50,421	4,253	5,109

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