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Research article

Quantifying future sanitation scenarios and progress towards SDG targets in the shared socioeconomic pathways

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ABSTRACT

Two main targets of SDG 6 (Sustainable Development Goal), clean water and sanitation, are SDG 6.2, to achieve universal and equitable access to improved sanitation and to phase out unimproved sanitation (include pit latrines without a slab or platform, hanging latrines, bucket latrines and open defecation) and SDG 6.3, to halve the proportion of untreated wastewater by 2030. We compiled a global sanitation database for 200 countries. Starting from recent trends, we constructed a wide spectrum of contrasting future scenarios, i.e. the five Shared Socio-economic Pathways (SSP1-5) whereby the SSP2 scenario is 'middle of the road' scenario. The sanitation scenarios differ due to contrasting pathways for population growth and urbanization, economic growth and the SSP narratives.

Our results indicate that it will be difficult to achieve the SDG 6 target. Target 6.2 on improved sanitation is expected to be achieved between 2070 and 2090 in SSP1, SSP2 and SSP5, while the target will not be achieved by 2100 in SSP3 and SSP4. Unimproved sanitation is projected to be phased out by 2070 in SSP1 and SSP5, or beyond 2100 in SSP3 and SSP4. The percentage of households with sewerage connection will be between 51% in SSP3 and 75% in SSP5 in 2050, and respectively 60% and 95% in 2100.

Target SDG 6.3 on improving wastewater treatment will be reached by 2030 only in SSP1, followed by SSP2 and SSP5 between 2040 and 2050, while in SSP3 and SSP4 this target is not reached by 2100. The developments in wastewater treatment, expressed as percentage nutrient removal, showed an increase from 14% in 2015 to 45% in 2050 and 80% in 2100 in SSP1. But in SSP3, the global percentage is expected to have hardly changed by 2050 and have declined to 12% by 2100 due to the population growth in Sub-Saharan Africa.

There is a major contrast between countries and regions. In the period between 2000 and 2015, although globally the percentage of people with unimproved sanitation declined, in 7% of the 200 countries the number of people with unimproved sanitation increased. Also, wastewater treatment globally improved, but in 16 countries it deteriorated. This inequality is particularly important in SSP3 and SSP4 where the lack of improved sanitation will continue till 2100.

1. Introduction

The emissions of sanitation systems are a major source of nutrients, pathogens and harmful inorganic chemicals in water (Strokal et al., 2021; Beusen et al., 2022). Emissions of pathogens have a serious impact on human health with high mortality due to waterborne diseases such as diarrhea and cholera (Prüss-Ustün et al., 2014; Ali et al., 2015; Vermeulen et al., 2019). Emissions of nutrients result in eutrophication in rivers, lakes and coastal waters (Beusen et al., 2016) with negative effects on biodiversity (Janse et al., 2015) and leading to hypoxia (Kemp et al., 2009) and harmful algal blooms (Lewitus et al., 2012). Inorganic chemical pollution can have a multitude of effects, and can be grouped on the basis of the aim/function of the chemicals (e.g. biocides, pesticides, pharmaceuticals or cosmetics) or their effect (e.g. cytostatica, endocrine disrupting agents) or their source (e.g. synthetically produced contraceptive pill versus naturally produced animal, human or plant

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hormones) (WHO, 2017). The type of sanitation and level of wastewater treatment are two of the major reasons of pollutant emissions into surface waters. Therefore, information on sanitation access worldwide, together with socio-economic development based scenarios are necessary to make assessments for future water quality.

Sanitation is defined as a multi-step process in which human excreta and wastewater are managed from the stage of generation up to the stage of ultimate disposal or utilization (Tilley et al., 2014). This definition includes containment, emptying, transport, treatment, recycling and disposal of the human waste (WHO and Unicef, 2021). Containment includes the sanitation facilities in or near houses, such as flush toilets (connected to a septic tank or sewerage system), pit latrines or open defecation. The sludge from pit latrines and septic tanks need to be removed and transported to the place of disposal. Excellent management and practice of all steps are essential to reduce health risks and environmental impacts (World Bank, 2016). For example, the sludge from a septic tank or latrine can be dumped on the land or in surface water or, alternatively, be buried in a landfill or treated in a wastewater treatment plant. But also events as flooding, whereby human wastewater contaminates surface water with high health risks, become more important with climate change (Sellers, 2020).

Safely managed sanitation services are defined as the use of an improved sanitation facility (pit latrines, septic tank, flush toilet) that is not shared with other households and where excreta is safely disposed of *in situ* or transported and treated off-site (in the case of flush toilets by a sewerage system or sludge from septic tanks) (WHO and Unicef, 2021). This means that the indicator includes the full sanitation service chain.

Nowadays, 54% of the global population lacks access to safely managed sanitation (WHO and Unicef, 2021). That means that fecal material is not properly managed and, depending on exposure, can cause health problems and environmental impacts, including eutrophication and ecosystem damage due to chemicals (Prüss-Ustün et al., 2014; Beusen et al., 2016). Access to sanitation is therefore a major factor determining the conditions for human health and ecosystem quality (UN, 2021).

The United Nations defined 17 Sustainable Development Goals (SDG), of which SDG3 (good health and well-being), SDG6 (clean water and sanitation) and SDG14 (life below water) are relevant for sanitation (UN, 2021). In particular SDG6 has specific targets for sanitation, i.e. target SDG 6.2 (by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation …) and target SDG 6.3 (by 2030, improve water quality by (…) halving the proportion of untreated wastewater …) (UN, 2021). The following indicators are defined for these SDGs: indicator 6.2.1, the proportion of population using safely managed sanitation services (…) and indicator 6.3.1 proportion of domestic and industrial wastewater flows safely treated (UN, 2021). It is clear that indicator 6.2.1 partly overlaps with indicator 6.3.1.

Data on the sanitation status in most countries is available from the Joint Monitoring Program (JMP) of WHO and UNICEF, which reports mostly on the containment part of sanitation. Emptying, transport and treatment of the effluent receive less attention within JMP (WHO and Unicef, 2019). The UN reports on indicator SDG 6.3.1 at the country level (WHO, 2022). In these reports most countries lack data on the transport and treatment of septic tank sludge. For 80% of the countries the provided estimate was based on assumptions made by WHO/Unicef when country reports are lacking.

Achieving the SDG targets 6.2 and 6.3 by 2030 is a challenging task, which requires a good overview of the gap between the goals and the current situation. Additionally, quantifying future sanitation development is required to understand long term developments on future health and environmental pollution, including water quality.

The Shared Socio-Economic Pathways (SSPs) are a set of scenarios developed to investigate long term developments and their effect on climate change (O'Neill et al., 2014; van Vuuren et al., 2014; O'Neill et al., 2017). These scenarios are based on narratives that describe plausible future trends (O'Neill et al., 2017). The five pathways, SSP1 – SSP5, have five different routes for future population, urbanization and prosperity (Table 1, S.I. 2). The pathways SSP1 and SSP5 have the lowest population growth, but respectively high to very high economic growth. SSP3 has lowest economic growth and highest population growth, SSP2 and SSP4 have medium population growth but differ in economic growth. SSP2 is the 'middle of the road scenario'. The SSP storylines include qualitative descriptions of access to health facilities, inequality, international cooperation, policy orientation, technological development and environment (Table 1). As these five SSPs are very different and all results are a consequence of population and economic growth, we added calculations with the SSP2 scenario to show the effect of different investments without changes in the socio-economic context.

Several recent studies aimed to assess future emissions of pathogens and nutrients to surface waters and the effects on health and water quality (Janse et al., 2015; Hofstra and Vermeulen, 2016; van Puijenbroek et al., 2019; Strokal et al., 2021; Beusen et al., 2022). These

Table 1
The key figures of the 5 SSP's that are relevant for future sanitation and wastewater treatment and the socio-economic parameters (a, based on O,Neill et al., 2017) and the development of population, urbanization and prosperity (b, see S.I. 2 for detailed information).

a)	SSP1	SSP2	SSP3	SSP4	SSP5
Access to health facilities, water, sanitation	High	Medium	Low	Unequal within regions,	High
Equality across and within countries	High	Medium	Low	Low	High
International cooperation	Effective	Relatively weak	Weak, uneven	Effective for globally connected economy, not for vulnerable populations	Focus on local environment with obvious benefits to well-being, little concern with global problems
Policy orientation	Towards sustainable development	Weak focus on sustainability	Oriented toward security	Toward the benefit of the political and business elite	Toward development, free markets, human capital
Technology: development and transfer	Rapid	Medium	Slow	Rapid development in high-tech economy, little transfer to poorer countries	Rapid
Environment	Improving conditions over time	Continued degradation	Serious degradation	Highly managed and improved near high/middle income countries, degraded otherwise	Highly engineered approaches, successful of local issues

b)		SSP1		SSP2		SSP3		SSP4		SSP5	
	2015	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Population (billion)	7.4	8.7	7.1	9.3	9.2	10.0	12.7	9.3	9.5	8.8	7.6
Urban population (%)	53	77	93	67	80	55	59	76	92	77	93
GDP (1000 US$/capita)	11	30	74	23	54	17	20	22	34	38	122

studies did not cover the full sanitation problem. For example, only the sewerage connections were included, or the historic situation was not included or the future changes were not linked to the socio-economic scenario drivers (van Puijenbroek et al., 2019; Strokal et al., 2021). Hofstra and Vermeulen (2016) made interpretations of the narratives for the extreme pathways SSP1 and 3, but limited to sewerage systems and open defecation, and neglecting the population with access to septic tanks and pit latrines.

The objective of this article is to evaluate the progress towards the achievement of SDG6 for two targets, target 6.2 (level of improved sanitation) and target 6.3 (level of wastewater treatment and management of septic tanks) in the 21st century using new sanitation scenarios that comprehend open defecation and the full sanitation service chain (latrines, septic tanks, flush toilets, safe waste disposal). This paper will describe the database developed for 200 countries for the period 1970–2015 based on JMP (WHO and Unicef, 2019), and the approach to project future developments using the economic growth data corresponding to each SSP scenario showing plausible developments.

2. Materials and methods

2.1. Database with sanitation and wastewater treatment

We compiled a database on four sanitation types for 200 countries or territories for the years 1970, 2000, 2010 and 2015 (see S.I. 8). In the Joint Monitoring Program (JMP), recent information was available for countries on the status of the coverage of four sanitation types, i.e. unimproved sanitation, pit latrines, septic tanks and sewerage connection (WHO and Unicef, 2019). Unimproved sanitation includes open defecation, pit latrines without slab, open pit, hanging toilet, bucket latrine and flush toilets to open drain. This information from JMP was available for 186 countries for the years 2000, 2010 and 2015. In case of missing years, the missing data could be interpolated from other years. For 14 small countries lacking information, the average of the corresponding world region was used (see S.I. 1). Historical data on sewerage connection for the year 1970 was based on previous studies (van Drecht et al., 2009; van Puijenbroek et al., 2019) and the other categories were extrapolated from the trend reported for the period 2000–2010.

Information on wastewater treatment was collected from several sources (WHO and Unicef, 2019; EEA, 2020; UNdata, 2020), but the definitions of the data were not consistent, even in data for single countries. For example, total treatment was either reported for the total country, or the urban areas or the population with a sewerage connection, and wastewater treatment could include or exclude primary treatment. Our approach includes a number of steps to achieve a consistent dataset.

First we combined several data sources. The dataset 'Population connected to wastewater treatment plants' of the European Union (EEA, 2020) was extended by interpolating between years to fill data gaps. Total treatment was based on JMP country estimates (WHO and Unicef, 2019). For some countries, additional information was available on total treatment (UNdata, 2020).

Wastewater treatment plants can have different levels of efficiency, e.g., primary, secondary, tertiary treatment. For future years the quaternary technology is distinguished, which is even more advanced and efficient that the tertiary technology and defined as a possible efficient, large scale wastewater treatment. The wastewater treatment types were grouped within each country in the classes primary, secondary and tertiary treatment based on the total wastewater treatment level in the following sequence: (i) the EEA information was used for the selected countries; (ii) the JMP country information (WHO and Unicef, 2019); (iii) less than 20% total treatment for whole countries was classified as primary treatment; (iv) for countries where no information was available from the above steps, the treatment types were based on the world region (S.I.1) or data from previous work were used (van Puijenbroek et al., 2019).

For a few countries with more than 20% total treatment and lacking information on the types of treatment (South Africa, Uzbekistan, Tajikistan, Uruguay, Syria, Democratic Republic of Korea, Taiwan and Argentina), the distribution over the wastewater treatment types was based on regional characteristics of the corresponding world region (see S.I. 1).

The resulting database is based on the available information in global datasets. These databases neglect information about the level of functioning of sewer systems and wastewater treatment plants, for example, a breakdown of sewer systems can have dramatic effects on the local health (Mason, 2009), therefore data on sewerage connection are sometimes unreliable as they show an opportunistic situation.

2.2. Sanitation and wastewater treatment model

The SSPs have been implemented with various integrated assessment models including the Integrated Model to Assess the Global Environment (IMAGE) (Stehfest et al., 2014; van Vuuren et al., 2017). To model the nutrient cycles on a global scale, the IMAGE model was extended with the Global Nutrient Model (GNM) (Beusen et al. 2016, 2022), which includes a sanitation model to compute urban nutrient emissions for the history and the SSP-scenarios.

In the previous version of IMAGE-GNM, the relationship between GDP and sewerage connection was used as a basis for scenario construction (van Puijenbroek et al., 2019). In the updated version presented here (Fig. 1), the development from unimproved sanitation to pit latrines, septic tanks and sewerage connection was (with a 10-year timestep) related to the country GDP. GDP data were taken from the SSP database (Riahi et al., 2017) and updated to include more recent years with data from the World Bank (World Bank, 2019). Missing data were added from UNSTAT (UNSTAT, 2019). For the future the OECD ENV-Growth model was used (Jiang and O'Neill, 2017, KC and Lutz, 2017; Leimbach et al., 2017; Gidden et al., 2019).

The model presented here uses equations describing the level of three sanitation characteristics as a function of GDP, i.e. i) sewerage connection, ii) sum of sewerage connection and septic tanks and iii) sum of sewerage connection, septic tanks and pit latrines (Fig. 2). These relationships were developed at the scale of IMAGE world regions (S.I. 1), and applied to individual countries respecting the situation and specific level in the base year.

On the basis of the GDP relationships, the share of sewerage systems was calculated:

$$p\_sewer_{country} = f\_sanition_{scenario} * 26.242 \ln\left(GDP_{country}\right) - 187.68\; p\_sewer\_corr_{country} \tag{1.a}$$

$$p\_sewer_{country} = \min\left(p\_sewer_{country}, \left(p\_urban_{country} + p\_rural_{country} / 2\right)\right) \tag{1.b}$$

whereby *p_sewer* is sewerage connection of total population (%); $f\_sanitation_{scenario}$ is a scenario specific factor with a default value of 1 (unitless) and a negative value results in a slower improvement of sanitation and a positive value in a faster improvement; and $p\_sewer\_corrr_{country}$ is a country-specific correction factor to match the 2015 situation (% of population), *p_urban* is the urban population (% of total population) and p_rural is the rural population (%). Sewerage systems were restricted to urban areas and only a fraction of the rural area can be connected. In this study, an assumption was that a maximum of 50% of the rural area can be connected to a sewerage system (S.I. 6 for effect of this parameter).

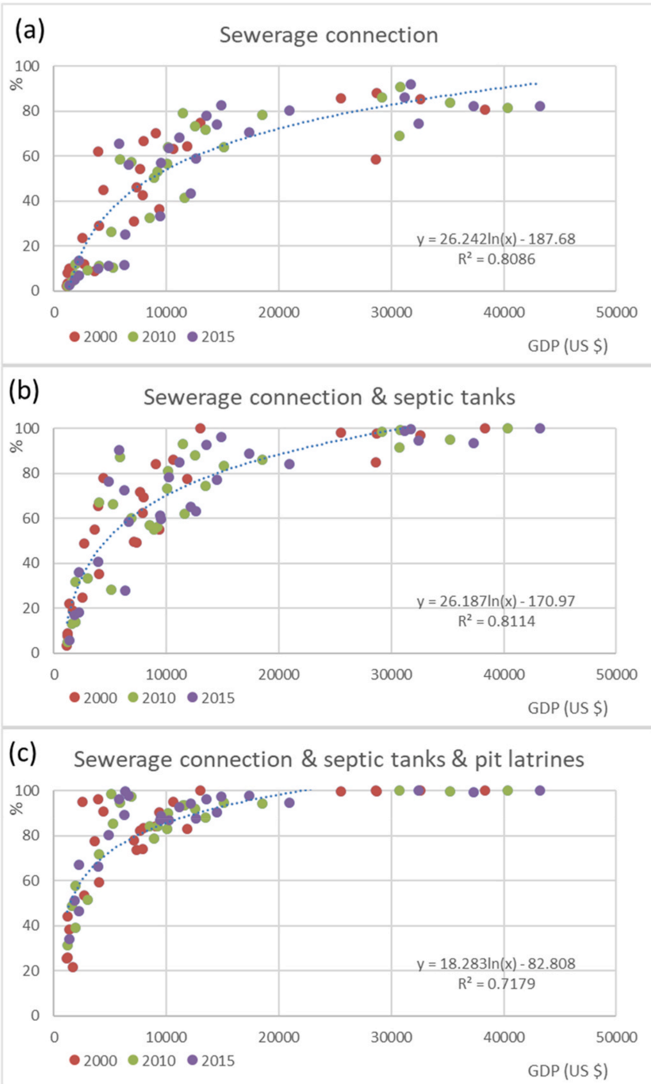

Fig. 1. The relationships between gross domestic products (GDP) and percentages of sewerage connections (a), septic tanks and sewer connection (b) and pit latrines in combination with sewer connection and septic tanks (c) for 27 IMAGE world regions (S.I. 1). The relationships were based on the data for the years 2000, 2010 and 2015.

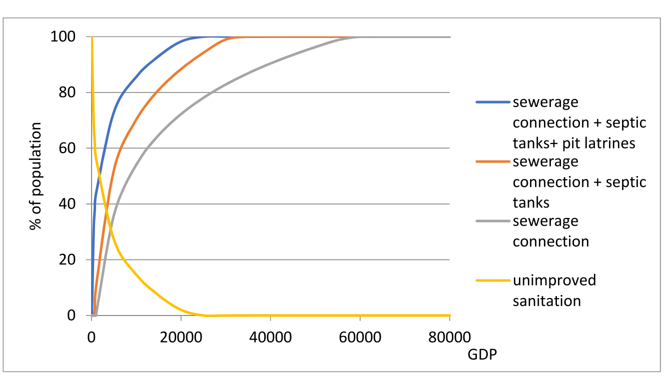

Fig. 2. The relationship between GDP and the total population with four types of sanitation. The relationships of Fig. 1 are combined with the unimproved sanitation.

Only countries with >50% connection in rural areas in 2015, such as The Netherlands and Austria, are assumed to maintain that level in future years. Reduction in the coverage of sewerage systems is not considered.

The percentage septic tanks, *p_septic*, was calculated with 'sewer + septic' minus the calculated sewerage connection, and also corrected with a country-specific correction factor.

$$p\_septic_{country} = f\_sanitation_{scenario} * 26.187 \ln(GDP_{country}) - 170.97 + p\_sept\_corr_{country} - p\_sewer_{country} \quad (2)$$

whereby *p_septic* is the share of septic tanks (% of total population) and *p_sept_corr* the country-specific correction factor. Next the percentage pit latrines, *p_pitlatrine*, is calculated with equation (3) based on the two previous calculations:

$$p\_pitlatrine_{country} = f\_sanitation_{scenario} * 18.283 \ln(GDP_{country}) - 82.808 + p\_pitlatrine\_corr_{country} - p\_sewer_{country} - p\_septic_{country} \quad (3)$$

whereby *p_pitlatrine* is the share pit latrines (% of total population) and *p_pitlatrine_corr* are the country-specific correction factor. The share of the population lacking improved sanitation (%) is calculated as the complement:

$$p\_unimproved_{country} = 100 - p\_sewer_{country} - p\_septic_{country} - p\_pitlatrine_{country} \quad (4)$$

Thereby, *p_sewer*, *p_septic* and *p_pitlatrines* are between 0% and 100% and the sum of the four types equals hundred.

The country-scale information was further downscaled to the urban and rural populations within countries. Urban and rural coverage was based on the SSP population data. The total population with a sewerage connection was first assigned to the urban population, and the remainder part of sewer connected people to the rural population. Where relevant, the population with unimproved sanitation, pit latrines and septic tanks were equally distributed over the urban and rural populations without sewerage connection.

The four types of wastewater treatment were aggregated to an overall percentage nutrient removal by wastewater treatment to allow for comparing different countries and evaluating scenarios. The wastewater treatment index is defined as

$$NR_{country} = 100 * \left(p\_primairy_{country} * 0.1 + p\_secondary_{country} * 0.4 + p\_tertiary_{country} * 0.85 + p\_quaternary_{country} * 0.95\right) \quad (5)$$

Whereby NR, Nutrient removal, is an index between 0% and the maximum possible nutrient removal based on the total population; *p_primary*, *p_secondary*, *p_tertiary* and p_quaternary are the shares (%) of primary, secondary, tertiary and quaternary treatment in a country based on the total population. The nutrient removal was calculated from the average of nitrogen and phosphorus removal for each treatment class (van Puijenbroek et al., 2019), (10% for primary treatment, 40% for secondary, 85% for tertiary and 95% for quaternary treatment).

Subsequently, we established a relationship between this overall nutrient removal and the country's GDP at the scale of IMAGE regions (Fig. 3, Appendix 1 for Image regions).

$$NR_{country} = \max\left(0.0013 * GDP_{country} - 0.9447 + NR\_corr_{country} + ww\_scenario\_corr_{year}, max\_nutrient\_removal_{scenario}\right) \quad 6)$$

Whereby *NR_corr* is a country-specific correction, *ww_scenario_corr* is a scenario specific correction factor (%) and *max_nutrient_removal* is the scenario specific maximum level of wastewater treatment).

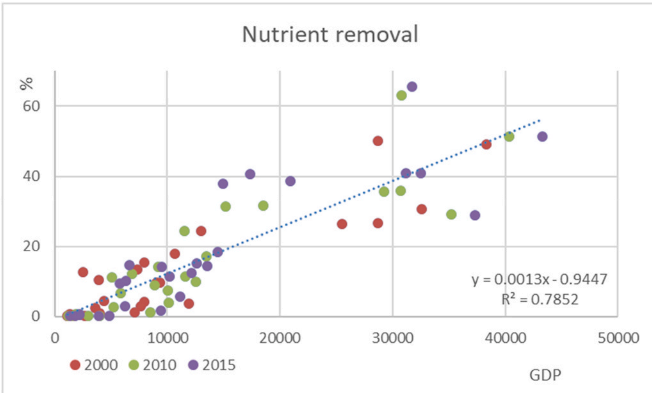

Fig. 3. Overall nutrient removal (NR, %) related to GDP in 2000, 2010 and 2015 for world regions (see S.I. 1).

2.3. Scenario characteristics

The main driver of this model is the development of the GDP in each country and in each scenario, which presents a spectrum of possible futures (Table 1). For wastewater treatment the following assumptions were made for each scenario (see also Table 2):

- SSP1 is a scenario focused on sustainability. In this scenario, the largest progress in wastewater treatment and sewerage connection will be realized. The management of on-site sanitation is good due to stringent environmental regulations.
- SSP2 is a middle of the road scenario, and there is less progress in sanitation improvement than in SSP1. Wastewater treatment is limited to tertiary treatment and the management of on-site sanitation is mostly moderate.
- SSP3 portrays a fragmented world where the policy orientation has less attention to environmental policies and due to less economic growth, sewage connection and wastewater treatment remain at a low level. Management of on-site sanitation is poor due to absence of environmental regulations. The lowest value for nutrient removal is 80% which is the target of the EU concerning urban wastewater (EEC, 1991).
- SSP4 is a scenario with high urbanization and inequality, therefore wastewater treatment has less attention and onsite sanitation has poor management.
- SSP5 is a conventional development scenario with high economic growth but with less attention to environmental aspects than in SSP1. The high economic growth leads to a larger coverage of sewerage connection to improve health for all, but the level of wastewater treatment is less than in SSP1, and the management level of on-site sanitation is moderate.

Management of septic tanks and pit latrines determines the local health effects. Good management includes septic tanks with a leach field which are periodically emptied, septic tanks and pit latrines are watertight and the sludge of septic tanks is transported to a wastewater treatment plant, the waste of pit latrines is buried or transported to a treatment plant. Poor management has none of one of these aspects. (See S.I. 5).

As the SSP scenarios are contrasting with regard to population, urbanization and prosperity, the differences due to improvement of access to sanitation are difficult to interpret. To disentangle the effect of improvement of sanitation per se, we analyzed three variants of the SSP2 scenario, whereby only the assumptions with regard to sanitation were varied. These variants, SSP2_low (SSP2_L), SSP2_medium (SSP2_M) and SSP2_high (SSP2_H) differ in the investment levels for improvement of sanitation and wastewater treatment, whereby all socio-economic parameters are equal. SSP2_M is the default SSP2 scenario, with all parameters resulting from the socio-economic developments (Table 2; Figs. 1–3). In SSP2_L, the improvement of access to sanitation and wastewater is slower than in SSP2_M; sewer connection on a global scale is a continuation of the trend from 1970 till 2015 (Table 2, Fig. 4). SSP2_H shows the effect of additional investments to increase the coverage of sewer connection and wastewater treatment than in SSP2_M.

The factor "improvement of sanitation access" ($f\_sanitation_{scenario}$) is included in the equations for calculating the coverage of sewerage systems, septic tanks and pit latrines (Equations (1)–(3); Table 2) to achieve the above contrasts between the three SSP2 scenarios. A high value of $f\_sanitation_{scenario}$ results in larger sewerage connection coverage due to reduction of the percentage inhabitants with unimproved sanitation. The other parameters that are different in the SSP2 scenarios are the maximum nutrient removal, the *ww_scenario_corr* and the management of on-site sanitation (pit latrines and septic tanks). Differences in the scenario assumptions between the SSPs are listed in Table 2. In general terms, the differences are as follows:

- SSP2_L has the slowest improvement in access to sanitation and wastewater treatment based on continuation of the 1970–2015 trend. Maximum nutrient removal in wastewater treatment is limited to tertiary treatment (80% nutrient removal). On-site sanitation is poorly managed due to lack of stringent environmental regulations.
- SSP2_M is the default SSP2.
- SSP2_H, has a faster improvement of the coverage of sanitation and wastewater treatment. The maximum nutrient removal is 90%, which is achieved by quaternary treatment. On-site sanitation is well-managed as a result of stringent environmental regulations.

These variants are a sensitivity analysis for the effect of the parameters *f_sanitation*, *max_nutrient_removal* and *ww_scenario_corr*. SSP2_L and SSP2_M are both plausible as prognoses, showing an uncertainty of the future deverlopments, while SSP2_H is more a plausible optimistic scenario.

2.4. SDG targets

The main goal of SDG 6 is to '*Ensure availability and sustainable*

Table 2
The scenario assumptions related to improvement of sanitation access and wastewater treatment.

	SSP1	SSP2_L	SSP2_M	SSP2_H	SSP3	SSP4	SSP5
Improvement of sanitation	medium	low	medium	high	medium	medium	medium
$f\_sanitation_{scenario}$ (see Eqs. (1)–(3))	1	0.6	1	1.3	1	1	1
Wastewater treatment	high	low	medium	high	low	medium, low	low
Maximum nutrient removal, (see Eq. (6))	90	80	85	90	80	80	80
Percentage change of access to wastewater treatment, $ww\_scenario\_corr_{year}$ (see Eq. (6))							
2020	1	−1	0	1	−1	0	−1
2100	20	−20	0	20	−20	0	−20
Management of septic tanks and pit latrines							
Pit latrines	good	poor	intermediate	good	poor	poor	intermediate
Septic tanks	good	poor	intermediate	good	poor	poor	intermediate

management of water and sanitation for all', whereby two targets are relevant to this study.

Target 6.2 is '<i>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</i>' and (UN, 2021). This target is worked out in indicator 6.2.1 '*Proportion of population using (a) safely managed sanitation services and (b) a hand-washing facility with soap and water*' (UN, 2021).

In this study, we evaluated indicator 6.2.1a of target SDG 6.2 at the scale of 10 world regions and on a global scale. The target of SDG 6.2 is to achieve improved sanitation for all in 2030 (WHO, 2016). If the scenarios result in 99% achievement of this target, we round off to 100% in view of the large uncertainties. Improved sanitation is further worked out and defined as *'the proportion of population that is using an improved sanitation facility, which is not shared with other households, and where the excreta produced is either:*

- *treated and disposed in situ,*
- *stored temporarily and then emptied and transported to treatment off-site,*
- *or transported through a sewer with wastewater and then treated off-site* (WHO, 2016)

We defined unimproved sanitation as follows:(i) sewerage connection without wastewater treatment; (ii) septic tanks and pit latrines with insufficient, poor management (see S.I. 5 for the criteria for poor management); (iii) unimproved sanitation.

Target 6.3 is defined as '*by 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally*' (UN, 2021). This target has two indicators, 6.3.1 '*Proportion of domestic and industrial wastewater flows safely treated*' and 6.3.2 '*Proportion of bodies of water with good ambient water quality*'; in this study we focus on indicator 6.3.1.

The criteria of SDG 6.3.1 are still under revision (UN Water, 2022). In this study, we used a modification of these guidelines: (i) at least primary treatment in case of low exposure, such as groundwater recharge or discharge to oceans. (ii) at least secondary treatment; (iii) well-managed septic tanks; (iv) focus on domestic wastewater. In arid zones we assumed that the liquid part of the excreta is drained by assuming mixing with the groundwater recharge. The population living in the arid zone is determined by overlaying population density with the arid region map used in the IMAGE model (Stehfest et al., 2014).

The target 6.3 is formulated as 'halving the proportion of untreated wastewater'. The evaluation of this target is based on the level of wastewater without treatment in 2010; when this level of untreated wastewater is halved, the target is met.

3. Results

3.1. Historical period 2000–2015

Globally, the percentage of the total population with unimproved sanitation declined from 38% to 20% between 2000 and 2015, and in all 10 world regions the percentage of the population with unimproved facilities declined. However, not all countries showed an improvement of sanitation access in this period (WHO and Unicef, 2019). In 16 countries (hosting 4% of the total population), the percentage of the population with unimproved sanitation even increased in this period (Table 3).

Population growth is an important factor. Taking this population growth into account reveals that 44 countries had an increase in the number of people with only unimproved sanitation. This results in an increase of 132 million people in these 44 countries with only unimproved sanitation. About 14% the global population lives in countries with a deterioration or a standstill in basic sanitation over the 2000–2015 period. The absolute and relative increase of unimproved sanitation was mostly in Sub-Saharan Africa (92%) and South and Southeast Asia (8%) (Table 3). The difference between absolute and

Table 3

Changes in unimproved sanitation (a) and wastewater treatment (b) between 2000 and 2015. Countries can have an absolute increase in the number of inhabitants lacking improved sanitation (a, left), or countries can have a relative increase in the percentage of inhabitants lacking improved sanitation (a, right). The changes in wastewater treatment between 2000 and 2015 are presented for the countries with already some wastewater treatment in 2010 (b, right) and those countries with hardly any wastewater treatment (b, left).

(a) Unimproved sanitation region	Countries with absolute increase		Countries with a relative increase	
	Number of countries	Population with unimproved sanitation (million)	Number of countries	Population with unimproved sanitation (million)
North America	0		1	0.1
Central - and South America	4	1.9	2	0.0
Middle East and North Africa	1	0.1	1	0.1
Sub-Saharan Africa	33	462.0	5	71.6
West and Central Europe	0		3	0.3
Russia and Central Asia	1	0.3	1	0.3
South Asia	1	16.8		
China Region	0		2	17.3
South East Asia	3	20.4	1	0.1
Japan and Oceania	1	0.1		
World	44	502.5	16	89.8

(b) Wastewater treatment	Number of countries with <10% nutrient removal			Number of countries with >10% nutrient removal		
	decrease	small increase (<1%)	Increase (>1%)	decrease	small increase (<1%)	Increase (>1%)
North America	1	0	1	1	0	1
Central - and South America	18	13	8	1	1	1
Middle East and North Africa	1	7	3	1	0	7
Sub-Saharan Africa	26	20	1	0	0	1
West and Central Europe	0	1	10	0	0	29
Russia and Central Asia	1	4	3	2	0	2
South Asia	1	6	0	0	0	0
China Region	0	1	2	0	0	1
South East Asia	4	5	1	1	1	0
Japan and Oceania	6	0	0	0	0	6
World	58	57	29	6	2	48
% of global population	15	34	31	1	0	19

relative increase showed that, e.g. in Sub-Saharan Africa, many countries were not able to compensate the population growth.

Wastewater treatment, expressed as nutrient removal, was also improved on a global scale between 2000 and 2015 from 9 to 14%. This improvement was not equally distributed. Fifty-six countries had already >10% nutrient removal in 2000 and most of them improved their wastewater treatment in the period up to 2015. In contrast, countries with <10% nutrient removal in 2000 showed no or only slight improvement. Half of the global population lived in countries with an improvement in wastewater treatment of more than 1% nutrient removal, while the other half lived in countries without any improvement.

This change in access to basic sanitation and wastewater treatment showed that global improvement is not equally distributed and that many countries with a high population growth cannot increase the access for an increasing fraction of the population. Many countries with no access to wastewater treatment showed no improvement of the coverage in the period 2000–2015. This inequality is not restricted to Sub-Saharan Africa, most world regions include countries with a standstill or deterioration of sanitation or wastewater treatment coverage (Table 3).

3.2. Scenario period 2015–2100

All scenarios project an improvement of sanitation access, although

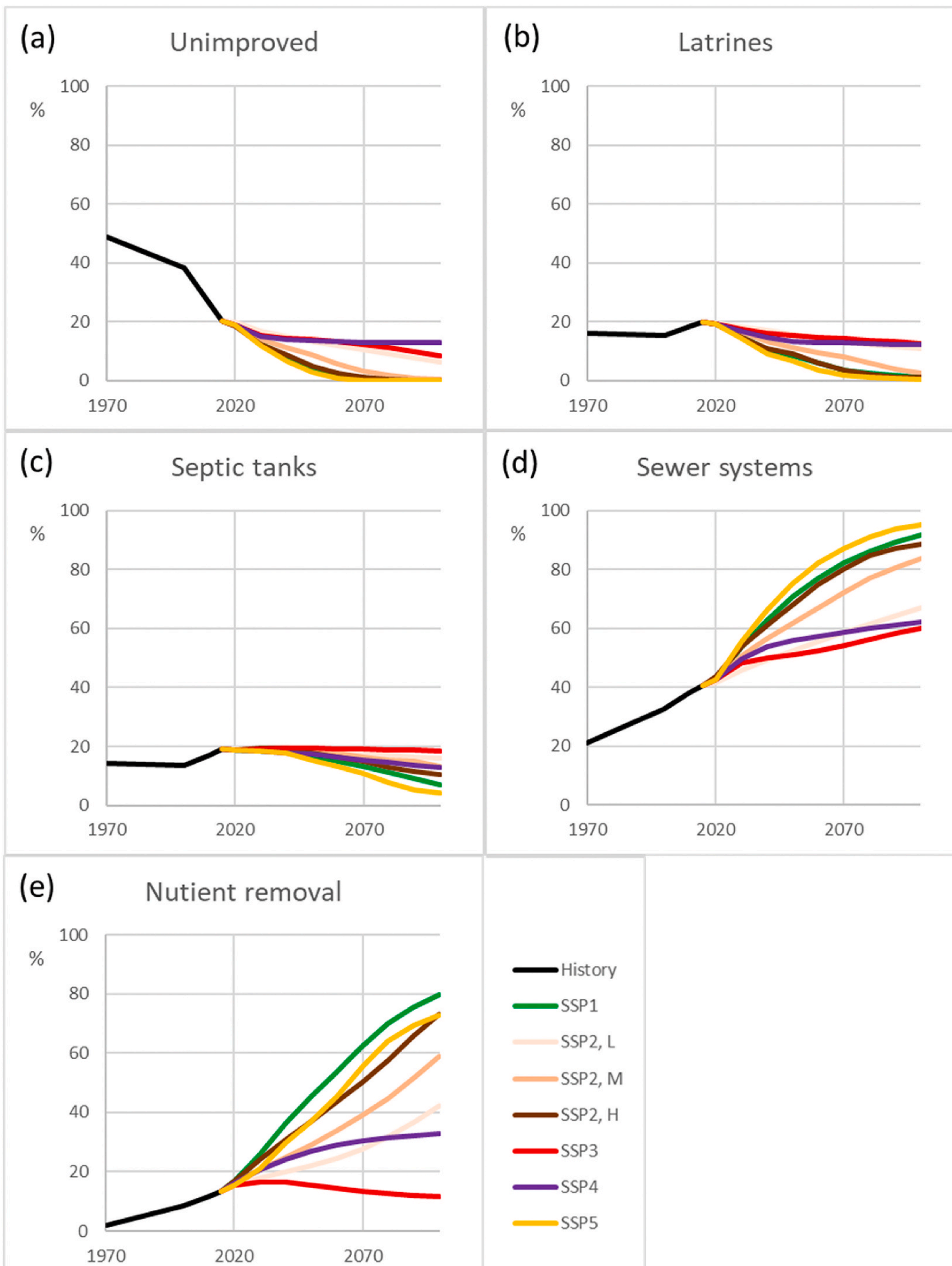

Fig. 4. The number of inhabitants with unimproved sanitation as % of total population (a), with access to pit latrines (b), septic tanks (c), and sewerage systems (d), and overall nutrient removal in wastewater treatment systems (see S.I. 3).

the progress in SSP3 and SSP4 is small (Figs. 4–7, S.I. 3, see datafiles with country results). The percentage of the total population with unimproved sanitation will decline from 20% in 2015 to 14% in SSP3 and SSP4 in 2050 and 9% and 13% in 2100 respectively. In SSP1, SSP2 and SSP5, the population lacking access to improved sanitation will decline to 3–9% in 2050 and 0% in 2100. The largest difference between the SSP scenarios is in the population with a connection to sewerage systems. Globally, SSP3 and SSP5 have the lowest (60%, SSP3) and highest (95%, SSP5) percentages in 2100. The deviation of the SSPs primarily reflects the differences in GDP and urbanization (Table 1).

In the period from 2000 to 2015, the absolute global number of inhabitants connected to sewerage systems increased by 2–3 billion, with a further increase to between 5.1 billion in SSP3 and 6.6 billion in SSP5. In 2100, the global number of inhabitants with access to sewerage systems will vary between 6.5 billion in SSP1 and 7.7 billion in SSP3 and SSP2. The lowest coverage and the largest number of people with a connection to sewerage systems in 2100 is seen in SSP3 as a result of the high population growth.

The global coverage of pit latrines declines in all scenarios, but in SSP3 and SSP4 this makes up a considerable part (11–13%) of the global population in 2100. In the other scenarios, pit latrines will have nearly disappeared in 2100 with a coverage of about 1% of the global

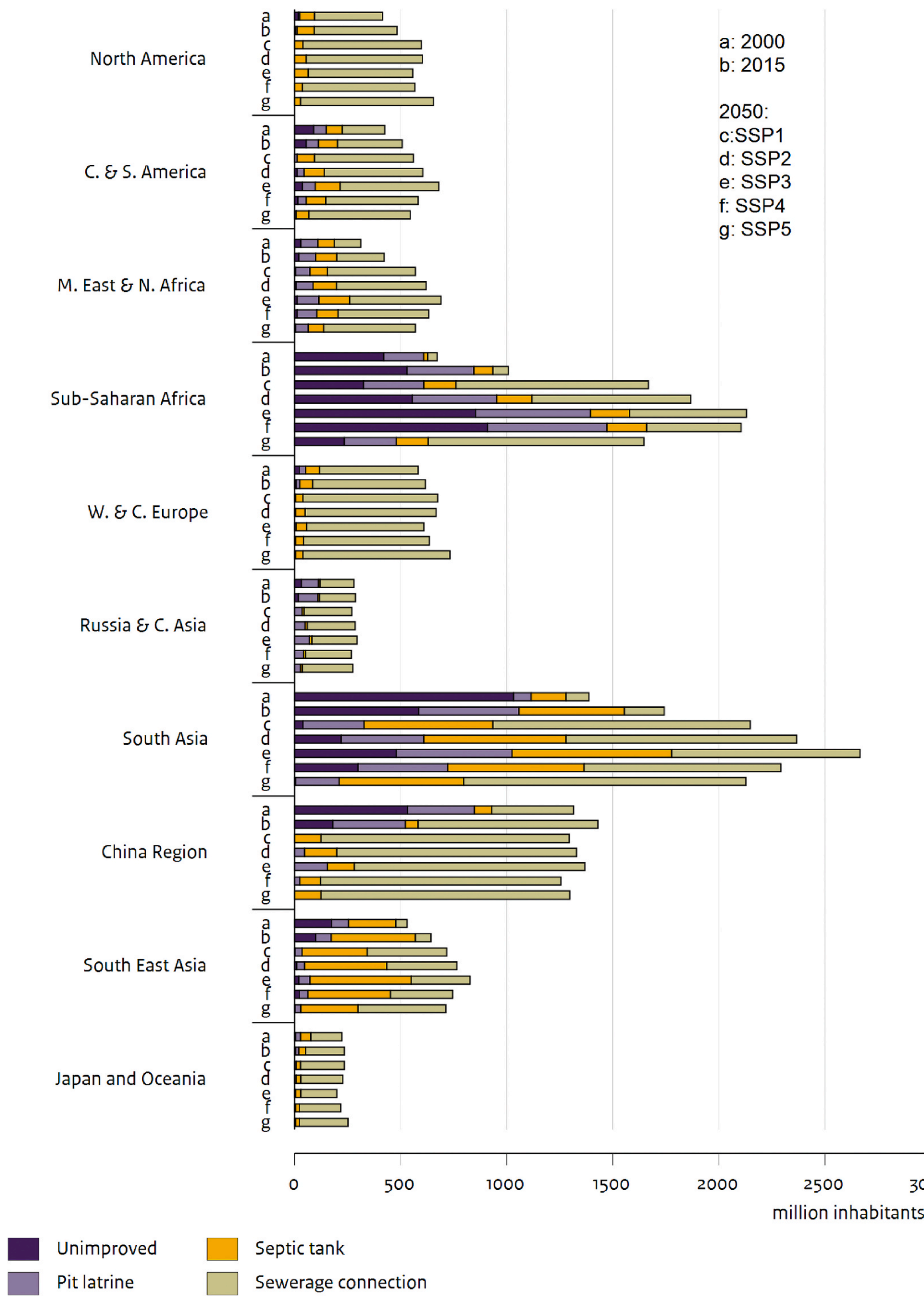

Fig. 5. Population with types of sanitation in 2000, 2015 and 2050 in 10 regions (see S.I. 3 for figure of 2100).

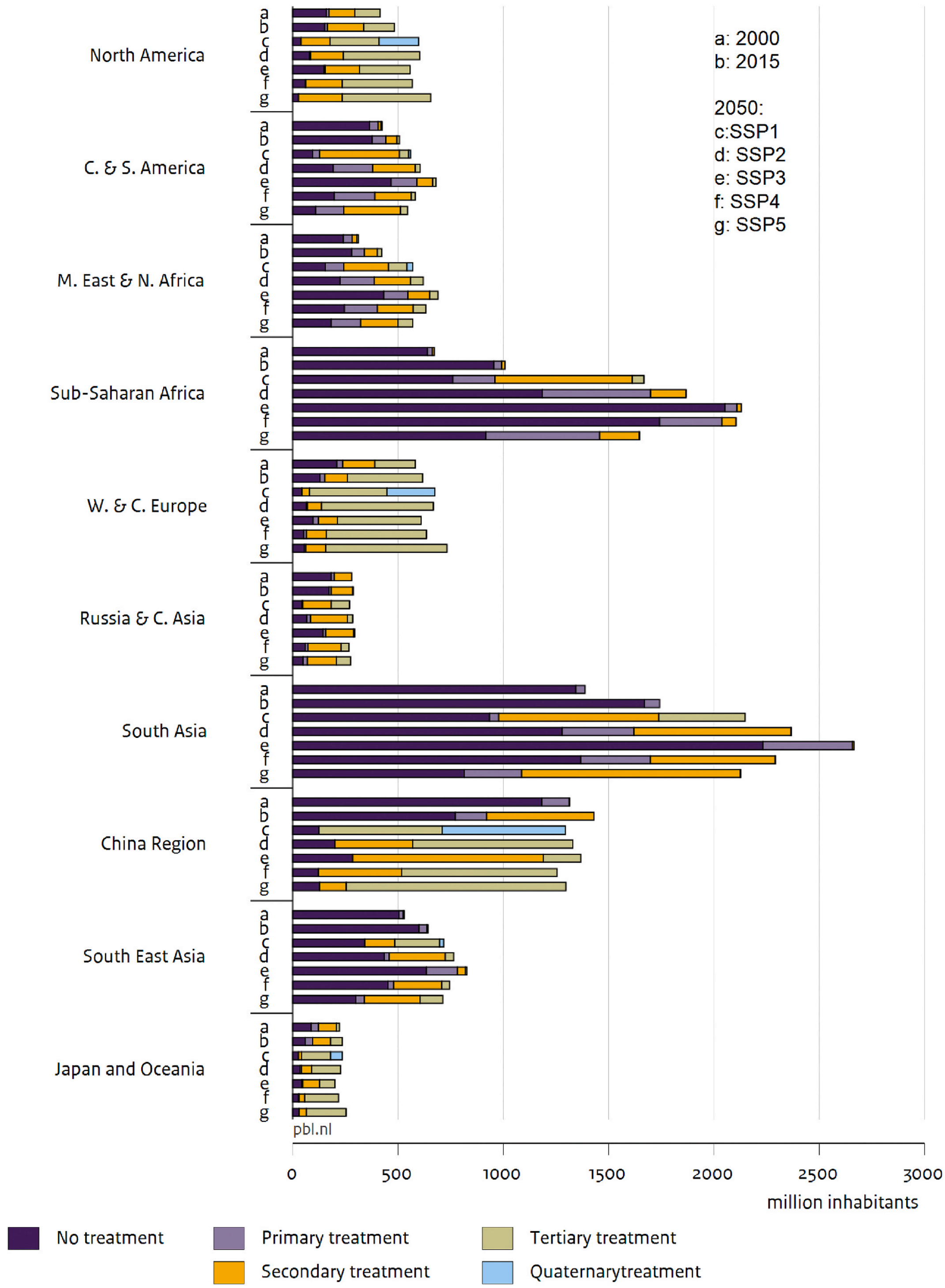

Fig. 6. Population with access to wastewater treatment in 2000, 2015 and 2050 in 10 regions.

population. The global coverage of septic tanks shows only slight changes between 2015 and 2050, and will decline to between 4% (SSP5) and 19% (SSP3) in 2100.

Wastewater treatment will show a strong contrast between the SSPs as a result of the differences in the prosperity and the storylines of the scenarios (Figs. 4, 6 and 8). In SSP3 and SSP4, a substantial part of the global population will live in low-income countries, with consequences for the global access to wastewater treatment. The population in Sub-Saharan Africa will increase from 14% of the global population in 2015 to 29% in SSP3 and 38% in SSP4 in 2100. Global nutrient removal in SSP3 will decrease (even though GDP is increasing in all regions of the world) due to an uneven distribution of population and economic growth. Population grows rapidly in Sub-Saharan Africa, parallel to a slow economic growth. The highest level of nutrient removal will be reached in SSP1 (high economic growth, focus on sustainable development), followed by SSP5 (less focus on sustainable development, but highest economic growth rate of all SSPs). In SSP5, all sewerage effluent is treated in plants with tertiary technology but no further progress to the more advanced quaternary technology.

The three SSP2 scenario variants portray the effect of different investment levels in sewerage systems and wastewater treatment. The global number of inhabitants with unimproved sanitation varies

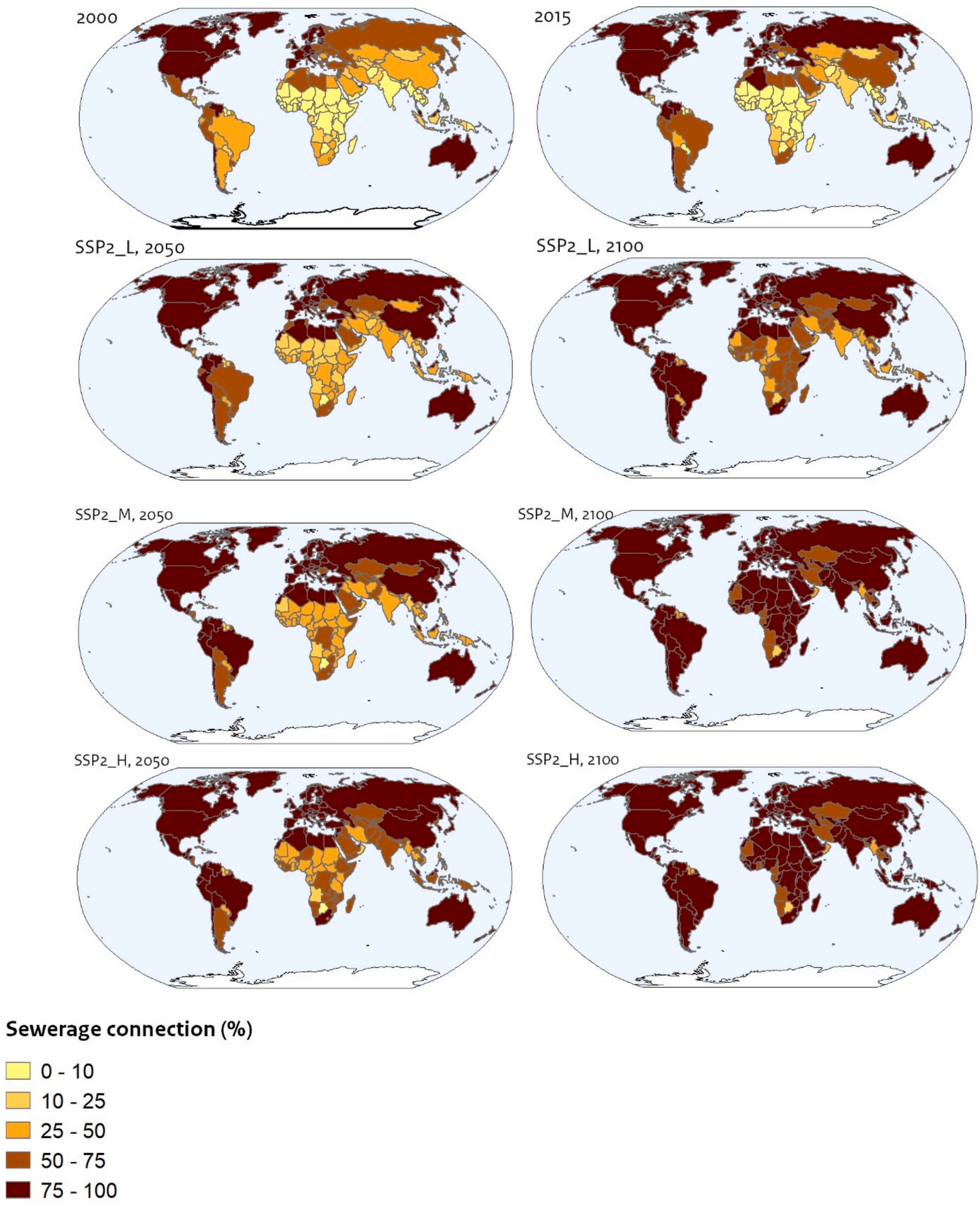

Fig. 7. Population with a sewerage connection for 2000, 2015 and for the three SSP2 scenario variants for 2050 and 2100.

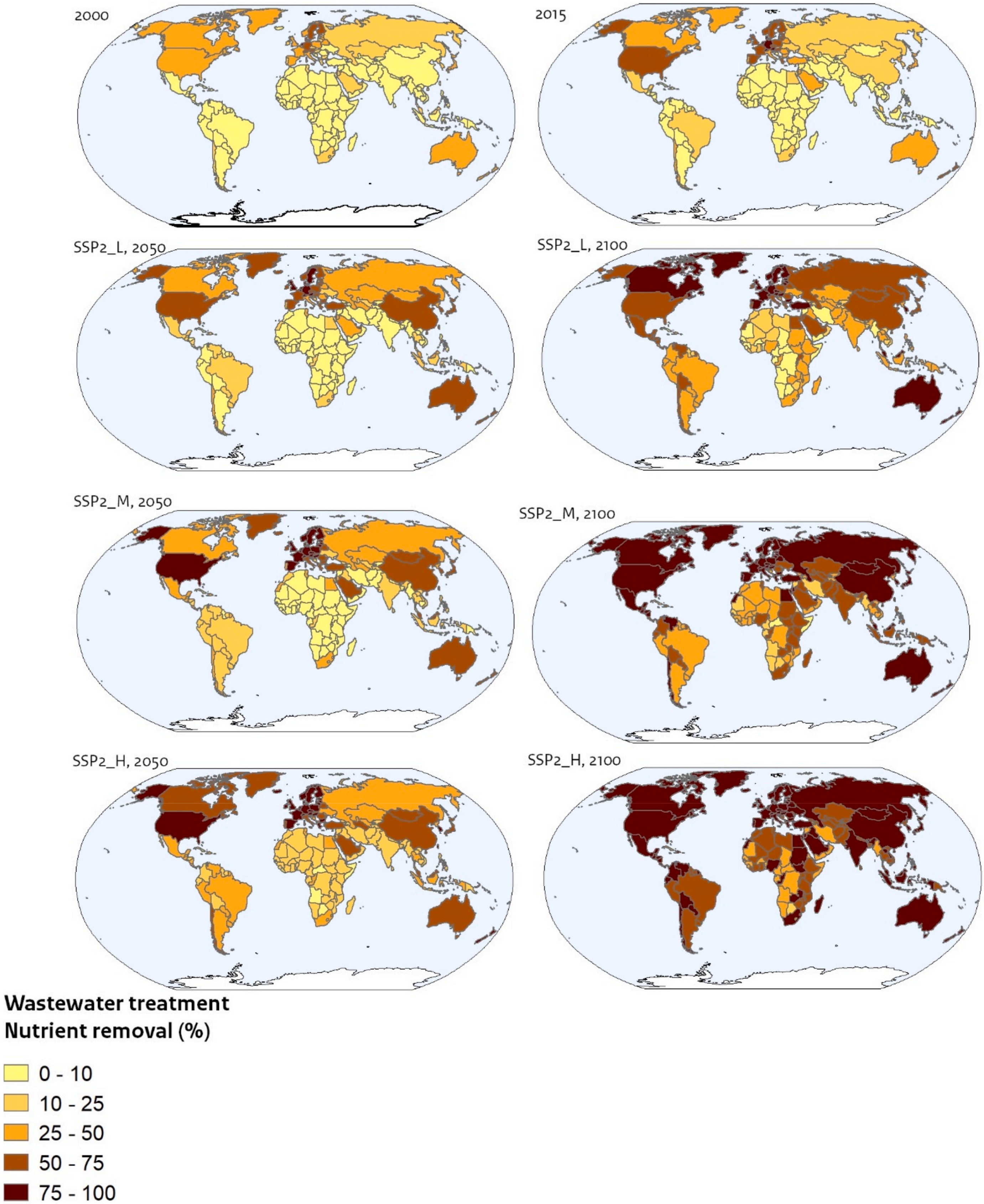

Fig. 8. Wastewater treatment expressed as nutrient removal for 2000, 2015 and for the three SSP2 scenarios for 2050 and 2100.

between 13% of total population in SSP2_L and 5% in SSP2_H in 2050. In the SSP2_L scenario, there is still unimproved sanitation in 2100. In 2050, the population connected to sewerage systems will increase by 1.9 billion in SSP2_L and 3.4 billion inhabitants in SSP2_H. In 2100, SSP2_H will have 2 billion people with a sewage connection more than SSP2_L. The variation in nutrient removal ranges between 22% and 37% in 2050 and 42% and 73% in 2100 on the global scale. This range is caused by a small, stepwise change in nutrient removal and difference in the maximum level of nutrient removal in the SSP2 variants.

3.3. Progress towards SDG 6.2 and 6.3

In the period 2000–2015, the number of world inhabitants with access to improved sanitation increased globally from 43% to 63% of total population, with major improvements in China and South East Asia (S.I. 4). The improvement of SDG 6.3 was less, globally the wastewater was safely managed in 22% of the global population which improved to 36%.

The global percentage of the population that have sanitation facilities according to SDG 6.2, showed progress in most scenarios (Fig. 9). Only in SSP3, the percentage of the global population meeting the target will decrease. On a regional scale, in SSP1, and some decades later in SSP5 and SSP2_H all regions will meet the target of SDG 6.2 between 2070 and 2100 (Table 4, S.I. 4). In the other scenarios, this target is not achieved by 2100. Therefore, the target of SDG 6.2, safely managed sanitation, will not be reached by 2030. Even in an optimistic scenario like SSP1, achieving the target globally will take several decades longer than envisaged. Especially in Sub-Saharan Africa it will take many decades to reach the target in the optimistic scenarios, while in the other scenarios this will not be met in 2100.

The indicator SDG 6.3.1 showed a faster progress towards the target (to halve the percentage without treatment) in most scenarios compared to indicator SDG 6.2.1. In SSP1 the target will be reached first, in 2030 (Fig. 9, Table 5). SSP2 and SSP5 reach the target between 2030 and 2050. In SSP3 and SSP4 with less economic growth, the target is not met before 2100. In all SSPs, Sub-Sahara Africa is the last region to reach the target. The global fraction of inhabitants for which SDG 6.2 and SDG 6.3 targets are achieved is dropping in SSP3 as a result of the low economic and high population growth.

This analysis shows that in SSP2_M, the ‘middle of the road’-scenario, the SDG 6.2 target on improved sanitation will be met after 2100. With an extra effort in sanitation in SSP2_H, this will be possible in 2080. As SSP2_L is based on the current trend, the target will not be reached in 2100. For SDG 6.3 the difference between SSP2_M and SSP2_H is about 10 year to reach the target, but the contrast with SSP2_L is larger. The regions Japan and Oceania, China, West and Central Europe and North America are the first regions to meet both SDG’s.

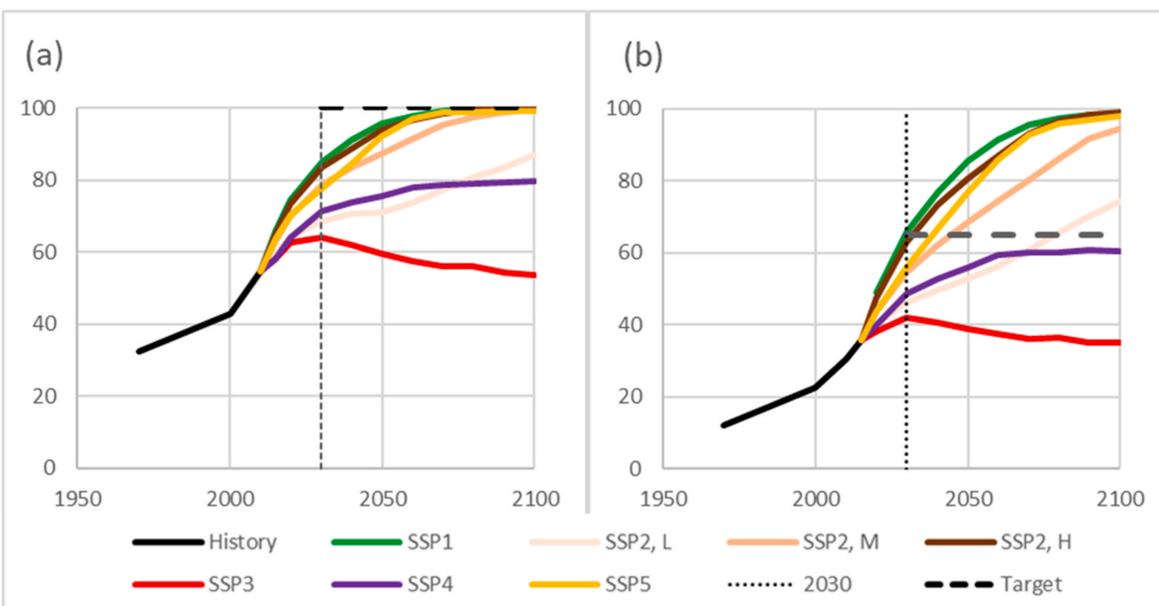

Fig. 9. Percentage of the global population with sanitation that meets the SDG 6.2 (a) and 6.3 (b) targets. The target for SDG 6.2 is 100% in 2030, for SDG 6.3, the global target is 65% of the population having safely managed wastewater.

Table 4
The first year that the target of SDG 6.2 is achieved for the SSPs for 10 world regions and the world. SDG 6.2 is more critical than SDG 6.3 as SDG 6.3 is faster to met.

	SSP1	SSP2, L	SSP2, M	SSP2, H	SSP3	SSP4	SSP5
North America	2040	2080	2060	2050	>2100	2060	2050
Central & South America	2050	>2100	2080	2060	>2100	>2100	2060
Middle East & North Africa	2050	>2100	2080	2050	>2100	>2100	>2100
Sub-Saharan Africa	2080	>2100	>2100	2090	>2100	>2100	>2100
West & Central Europe	2050	2100	2070	2060	>2100	2070	2070
Russia & Central Asia	2040	>2100	2070	2050	>2100	2070	>2100
South Asia	2060	>2100	2070	2060	>2100	>2100	2050
China Region	2030	2050	2030	2030	2040	2030	2030
South East Asia	2050	>2100	2070	2060	>2100	>2100	2050
Japan & Oceania	2040	>2100	>2100	2050	>2100	>2100	>2100
World	2070	>2100	2100	2080	>2100	>2100	2090

Table 5
Population with access to wastewater treatment and safely managed septic tanks, the SDG 6.3 target and the year that this goal will be achieved in the SSPs for 10 world regions and the world.

	Population (%)		Year in which SDG 6.3 is achieved						
	2010	SDG 6.3.1 target	SSP1	SSP2, L	SSP2, M	SSP2, H	SSP3	SSP4	SSP5
North America	78	89	2030	2050	2040	2030	>2100	2040	2040
Central & South America	23	62	2040	2080	2060	2040	>2100	2060	2050
Middle East & North Africa	43	71	2030	2080	2040	2030	>2100	2060	2040
Sub-Saharan Africa	4	52	2050	2100	2070	2060	>2100	>2100	2060
West & Central Europe	81	90	2030	2040	2030	2030	2080	2030	2030
Russia & Central Asia	38	69	2030	2060	2040	2040	>2100	2040	2040
South Asia	10	55	2040	2070	2050	2040	>2100	2060	2040
China Region	26	63	2020	2030	2020	2020	2030	2020	2020
South East Asia	26	63	2030	2050	2030	2030	>2100	2050	2030
Japan & Oceania	68	84	2030	2030	2030	2030	2030	2030	2030
World	30	65	2030	2080	2050	2040	>2100	>2100	2040

4. Discussion

4.1. Contrasting scenarios

Our sanitation futures are plausible scenarios based on very different socio-economic scenarios. The plausibility of the scenarios was based on the historical changes in the last 15 years, which showed that progress is not equally distributed, as there are countries with improving sanitation levels, but there are also countries without any progress or standstill (Table 3). For wastewater treatment, this analysis of the historical development showed that most countries with wastewater treatment had improved their wastewater treatment, but that a major part of the countries without wastewater treatment did not show progress in the past 15 years. This aspect is implemented in the correction factor for wastewater treatment.

The effect of population growth and economic growth are included in the main socio-economic drivers, whereby the scenarios with highest population growth (SSP3) has the lowest economic growth and opposite, SSP5 and SSP1 have lowest population and highest economic growth. Therefore, the combination of relative changes (Fig. 4) and absolute changes (Figs. 5 and 6) are important to evaluate the progress towards improved sanitation. For example, SSP3 has the slowest progress of sewerage connection as a percentage of the population, but the number of people connected to sewers will be the highest in this scenario due to the fast population growth. This is a result of the characteristics of the SSP scenarios and the approach based on a relationship between GDP and the improved sanitation types (sewer, septic tank, pit latrine).

Another example is SSP5. In this scenario, according to the storyline, there is a reactive attitude towards environmental problems, with a slow change in the fraction of the population with access to wastewater treatment (Eq. (4), Table 2). However, SSP5 is a scenario with the most rapid economic growth of all SSPs, and since also wastewater treatment is related to GDP, by 2100 all sewerage effluent is treated in wastewater treatment plants with a maximum tertiary treatment. This could be plausible, as health issues are a focus for SSP5, but without a policy towards sustainable development, no quaternary wastewater treatment will be realized.

SDG target 6.3 will be achieved sooner than 6.2. These two targets differ, as 6.2 is a health-based target focused on 'the whole population has improved sanitation' while SDG 6.3 is an ecosystem-based target that aims to 'halve the fraction of untreated wastewater'. This means, that even when the target 6.3 is reached, still a major part of the sewerage effluent is discharged untreated or after limited treatment, posing risks to the ecosystem and human health in the future. Ecosystem and health risks are expected to be particularly large in Sub-Saharan Africa followed by South Asia, regions where the burden of diarrhea related to Water Sanitation and Hygiene (WASH) is already very large (Troeger et al., 2017), and also jeopardizing SDGs 3 on health and 14 on 'life below water' and many others (Wang et al., 2022). Therefore, extra investments in wastewater treatment above necessary for achieving SDG target 6.3, are needed to reduce the human health and ecological effects in all scenarios.

This effect of more or less investments in sanitation and wastewater treatment is demonstrated by the contrast between SSP2_L and SSP2_H. For sanitation, the number of inhabitants for which SDG target 6.2 is achieved in 2050 ranges from 71% of total population in SSP2_L till 94% in SSP2_H. In 2100, in SSP2_L the target is achieved for 87% of the total population, leaving still 0.55 billion people with unimproved sanitation. The differences in wastewater treatment show more contrast between the SSP2-variants. In 2050, the global population with primary, secondary and tertiary treatment in SSP2_L are 0.8, 1.6 and 1.5 billion people respectively, together 3.9 billion people. In SSP2_H this is 0.7, 3.1, 2.0 respectively, and 0.4 billion with high technological quaternary treatment, together 6.3 billion. These differences result in an increase in nutrient removal globally to 22% in SSP2_L and 37% in SSP2_H. The global investments in wastewater treatment are high due to the rapid population growth and the improvement in wastewater treatment. These differences depend on the storylines, reflecting the political willingness to invest in the reduction of health and ecosystems risks.

On a regional scale, these results show that Sub-Saharan Africa and South Asia will still face a situation without adequate sanitation for a long time, even in the SSP1 scenario with high economic growth and proactive attitude towards environmental problems. The SDG 6.2 target for these regions will be met in 2080 and 2060 respectively, and in the other scenarios much later (Table 4). The contrast between the regions in the achievement of the SDG targets is smallest in SSP1, which is in line with the storyline of exchange of knowledge on technology and equality, while in SSP4 and SSP5 the divergence is much larger. Also for the time needed to achieve SDG 6.3, the contrast between regions is only 30 years in SSP1 and 80 years in SSP4.

The presented scenarios have three specific aspects: (i) they are based on the historic trend in sanitation and wastewater treatment and therefore much attention was given to develop the historical database with country data; ii) the scenarios were based on the future socio-economic developments in the scenarios; (iii) the storyline was translated to changes in sanitation and wastewater treatment in the future. These scenarios are already in use for the development of water quality scenarios by the World Water Quality Alliance, for use in the world water quality assessment (UN Water, 2016; World Water Quality Alliance, 2021). The data are available in the supplementary information for use in other projects (S.I. 8). We envisage future analyses of required investment to achieve SDGs 6.2 and 6.3. Moreover, information on sanitation and wastewater treatment is important in many other studies, such as burden of disease studies (Troeger et al., 2017), evaluation of methane emissions from onsite systems (Reid et al., 2014; Johnson et al., 2022) and future outlooks for these environmental issues related to wastewater.

4.2. Limitations and options for improvement

The Joint Monitoring Program (JMP) (WHO and Unicef, 2019) is a major data source for this study with data for most countries. The JMP database includes all available reports for each country, which involves differences in definitions missing data. Although there is much progress in improving these global databases during the last two decades, the differences in definitions are a point of concern.

One of the scenario assumptions is the stepwise improvement from unimproved sanitation, to pit latrines, septic tanks and sewerage systems. This assumption was based on the observed development in the past 15 years in many countries. However, in dryland areas with water shortages, or in rural areas, sewerage systems are not necessarily the best solution with lowest risks to ecosystems and human health (Beusen et al., 2022). Properly managed pit latrines, in particular in rural areas, may be more effective in avoiding eutrophication of surface water than sewers with limited wastewater treatment. Hence, our assumed stepwise improvement towards sewerage connection may have led to an overestimation of the fraction of sewers compared to well-managed pit latrines or septic tanks. However, since well-managed on-site systems and sewers are included in the improved sanitation definition for SDG indicator 6.2.1, this will not influence our evaluation of the progress towards the SDG.

Another assumption is that economic growth results in more wastewater treatment with a stepwise improvement from no treatment to primary, secondary, tertiary and quaternary treatment. This stepwise improvement is not always the case. Some European countries with high GDP did not invest in wastewater treatment until a common EU policy was implemented to force the investments in wastewater treatment (EEC, 1991; EU, 2020).

However, these differences are included in the storylines of the SSPs, whereby the SSP1 sustainability scenario projects more advanced wastewater treatment and higher maximum nutrient removal than the other scenarios (Table 3). Hence, environmental policy is an important factor for the implementation of wastewater treatment systems. In addition, pond or lagoon systems for storing and treating wastewater are a common practice which requires less investments than conventional waste water treatment systems (Grady et al., 2011). When managed in a good manner, pond and lagoon systems can efficiently treat the wastewater. Including these systems in our approach would improve our scenario assessment for a number of countries.

Our approach assumes that wastewater treatment plants will be effectively functioning immediately, while in practice there may be a lag time. Further typical scenario assumptions that are uncertain are the maximum sewerage connection and nutrient removal. The maximum connected rural area (Eq. (1.b)) was 50% in this study resulting in globally 84% sewerage connection in 2100, when this fraction rural connection varied between 10% and 90%, the sewerage connection would vary between 80% and 87% (S.I. 6). However, as urbanization is rapid in all scenarios, this factor is of limited importance.

The evaluation of both SDG targets are based on the level of four sanitation types, sewerage connection and the management of septic tanks and pit latrines. SDG 6.3 was compared with recent available country data, showing good results (S.I. 7.)

5. Conclusion

In the period 2000–2015, the population with access to improved sanitation increased globally. However, this did not occur in all countries, especially not in countries with rapid population growth. Also wastewater treatment improved globally, but half of the global population lived in countries with hardly any improvement in wastewater treatment during 2000–2015.

The scenarios show a range from a near standstill in SSP3 to much improved sanitation and wastewater treatment in SSP1. The scenarios show that unimproved sanitation will be phased out in SSP1, SSP2 and SSP5, but still be present in SSP3 and SSP4 in 2100. Wastewater treatment will vary in 2050 from 15% nutrient removal in SSP3 till 45% in SSP1. Especially Sub Saharan Africa and Southeast Asia lag behind, particularly in SSP3 and SSP4 with hardly any wastewater treatment.

We analyzed the progress towards achieving SDG targets 6.2 (improved sanitation for all world inhabitants by 2030) and 6.3 (halving the proportion of untreated wastewater by 2030). Our results indicate that SDG 6.2 will be achieved first in SSP1 in 2070, in SSP5 in 2090 and in the other scenarios the target is not met before 2100. SDG 6.3 will be achieved by 2030 in SSP1, followed by SSP5 in 2040 and SSP2 in 2050, but for SSP3 and SSP4 the target is not met before 2100. Due to rapid population growth and lagging economic growth, Sub-Saharan Africa is projected to achieve both targets about a half century later than high-income countries.

Achieving the SDG 6.3 target of halving the proportion of untreated implies that discharge of untreated wastewater will still be a problem and that associated ecosystem and human health risks will persist in the future. Our analysis highlights the importance of assessments of future access to sanitation and wastewater treatment, with consequences for the health situation of a large proportion of the world's inhabitants and surface water quality and eutrophication of aquatic ecosystems.

Credit author statement

Peter van Puijenbroek: conceptualization, methodology, formal analysis, validation, visualization, writing original draft, Arthur Beusen: methodology, Lex Bouwman: methodology, review and editing, Tolga Ayeri: analysis, Maryna Strokal: methodology, Nynke Hofstra: investigation, methodology, review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

I have shared the data of my results

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118921.

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