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SANITATION AND WASTEWATER TREATMENT SCENARIOS AND EFFECTS ON GLOBAL WATER QUALITY AND SDG 6

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21 December 2023

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The Hague, 2023
PBL publication number:

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Acknowledgements
We would like to thank Nynke Hofstra for calculating the emissions of pathogens, Arthur Beusen for calculating the emissions of nutrients and Jarl Kind for advice on the calculations of costs for sanitation.

Production coordination
PBL Publishers

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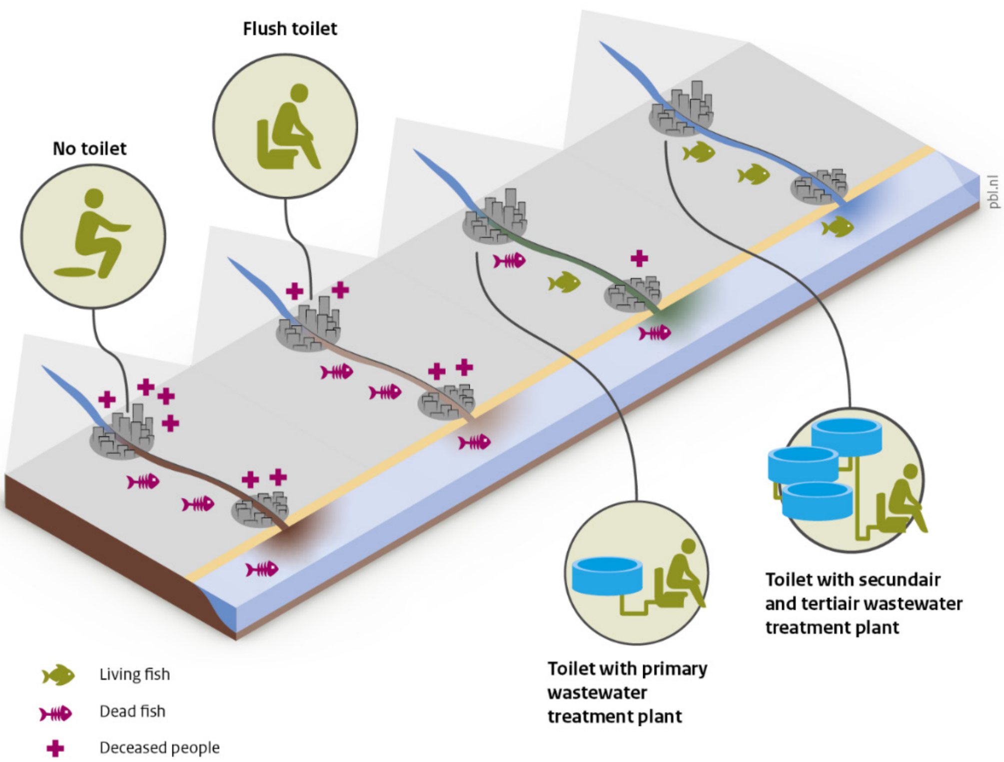
Summary

Sanitation and wastewater treatment are key elements for global human health and aquatic biodiversity. Based on a database with 200 countries, historical trends show an overall improvement of sanitation and wastewater treatment, but this improvement is inequal between countries.

Wastewater treatment and the effect of waste water



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A scenario study was based on the ‘Middle of the Road scenario of the Shared Socio-economic Pathways’ (SSP2) whereby the relation between economic growth, population growth and storylines of the scenarios with sanitation was used. Future analysis for sanitation and wastewater treatment showed an increase in sewerage connection and wastewater treatment, but different in each region of the world depending on prosperity and policy.

The effects of sanitation and wastewater treatment were calculated as emissions of waterborne pathogens and nutrients. Local pathogen emissions decrease as a result of a reduction of unimproved sanitation, but downstream pathogen emissions increase with an increase of sewer systems without sufficient wastewater treatment. Nutrient emissions to surface water increase overall as a result of an increase of sewer systems without sufficient wastewater treatment.
The Sustainable Development Goal (SDG) 6, clean water and sanitation, has two main targets. SDG 6.2, to achieve universal and equitable access to improved sanitation and to phase out unimproved sanitation and SDG 6.3, to halve the proportion of untreated wastewater. Both SDG targets will not be met in 2030, but much later depending on the investments in sewer systems and wastewater treatment.

1 Introduction

Sanitation and wastewater treatment are key elements for human health and aquatic ecosystem quality. Human health is vulnerable to waterborne diseases whereby on a global scale especially children are very vulnerable with high mortality (Prüss-Ustün et al. 2014). But also in many cities without sufficient wastewater management, the smell of wastewater affects local quality. The negative effect of wastewater is not limited to the location of production, but negative effects are also downstream in rivers and coastal seas. When wastewater is transported by sewer systems to rivers without sufficient wastewater treatment, this results in oxygen depletion, eutrophication and high pathogen levels affecting ecosystems and human health.

To avoid negative effects of human wastewater, household sanitation systems can be improved with flush toilets connected to septic tanks or sewer systems whereby the effluent of sewer systems and the containment of septic tanks have to be treated in wastewater treatment plants. Sewer systems are the very expensive, underground, and therefore not visible, infrastructure of cities. Wastewater treatment plants are, depending on the level of treatment, also expensive. The investments needed for wastewater are long term, large scale and expensive investments to improve local and global water quality and human health.

The United Nations 2030 Agenda for Sustainable Development includes 17 Sustainable Development Goals (SDG). SDG 6 is focused on clean water and sanitation. But the effects of wastewater is not limited to SDG6, also other SDGs are substantially affected by wastewater.

In this study, the middle of the road scenario of the Shared Socio-economic Pathways (SSP2) was worked out with different ambition levels (O'Neill et al. 2014, van Vuuren et al. 2014, O'Neill et al. 2017, PBL 2023) whereby the developments in sanitation and wastewater treatment were calculated and evaluated in the next steps:

- make scenarios of 4 sanitation groups and wastewater treatment;
- calculate the costs of sewerage systems and wastewater treatment;
- calculate the emissions of pathogens;
- calculate the emissions of nitrogen and phosphorus;
- evaluating the scenarios for SDG 6.2 and SDG 6.3.

1.1 Sanitation and wastewater treatment

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. Good management and practice of all steps are essential to reduce health risks and environmental impacts (World Bank 2016). For example, the sludge from pit latrines and septic tanks needs to be removed and transported to the place of disposal, or the pit latrines should be covered and a new one dug. The sludge from a septic tank or latrine can be buried in a landfill or treated in a wastewater treatment plant or, alternatively when no good management is practiced, dumped on the land or in surface water.

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 safely managed sanitation includes the full sanitation service chain. The four most important groups of sanitation are unimproved sanitation, pit latrines, flush toilets connected to septic tanks or sewer systems.

Wastewater treatment is needed for the effluent of sewer systems. There are three major kinds of wastewater treatment used: primary, secondary and tertiary. Primary treatment is focused on the reduction of the oxygen demand in the effluent to reduce 'dead water', this is surface water, i.e. rivers or seas, without sufficient oxygen for biota to survive. Secondary treatment removes also a part of the nutrients and pathogens, but more nutrients and pathogens are removed by tertiary treatment. In this study, we also distinguish quaternary treatment, which is defined as a future type of treatment with high removal of nutrients and pathogens which can be realized on a large scale with low costs of energy and space.

In this study, a database was developed with data of 200 countries for the period 1970-2015. This database was used to parameterize the model and to evaluate the historical changes.

1.2 Sanitation and health

Sanitation is extremely important for human health. Diarrheal diseases are related to inadequate Water, Sanitation and Hygiene (WASH). Diarrheal diseases are still a very important cause of death in children under 5 years old, with globally 297,000 WASH attributable deaths in 2016 (Prüss-Ustün et al. 2014). Pathogens, such as *Shigella* spp, rotavirus, adenovirus, *Cryptosporidium*, *Campylobacter* and pathogenic *E. coli*, are important causes of diarrheal diseases (Liu et al. 2016). To reduce the number of deaths and improve human health, SDG 6.2 is focused on the improvement of sanitation to improve local health. But downstream emissions of untreated wastewater are also a risk for human health. This is especially a risk for use of water for irrigation, recreation or drinking water. As most irrigated agriculture is located downstream of urban areas, the irrigated water polluted with human pathogens will be a risk for people working in irrigation systems (Thebo et al. 2017). About 885 million people live in downstream polluted irrigated areas

In this study we calculate the number of *Cryptosporidium* oocysts (spores) that reach the surface water through sanitation systems (Hofstra and Vermeulen 2016, Vermeulen et al. 2019). *Cryptosporidium* is a pathogenic protozoan parasite and is a leading cause of diarrhea worldwide. The concentration of Cryptosporidium in the surface water is a determinant for probability of exposure and the risk of disease. The oocysts in the surface water can cause disease in the population when people are exposed to that water, through drinking, bathing, eating fresh food produced with contaminated water, and other exposure routes. So while the emissions simulated in this paper do not indicate direct risk, they are an indication of surface water pollution for pathogens and of potential health risks.

1.3 SDG 6

Sanitation and wastewater treatment are related to SDG 6, whereby the main goal is to '*Ensure availability and sustainable management of water and sanitation for all*'. Two targets are relevant to this study.

Target 6.2 is '*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*' 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 target SDG 6.2 at the scale of 10 world regions and on a global scale (See 6.1). The target of SDG 6.2 is to achieve improved sanitation for all in 2030 (WHO 2016). 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; (iii) unimproved sanitation (Van Puijenbroek et al. 2023). In this study, we round off 99% achievement of this target to 100% in view of uncertainties in case of a uncertain, small part of the population with 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 (UN Water 2022). In this study, we used a modification of this guideline: (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. 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).

Target 6.3 is formulated as 'halving the proportion of untreated wastewater'. This target is evaluated as the first year when halve of the percentage of the population without treated wastewater in 2010, had treated wastewater.

1.4 Scenario Business-as-usual (BAU) and the ambitions to bend the trend

Future developments of sanitation and wastewater treatment are based on the global trend between 2000 and 2015 and the population growth and economic development of the SSP2 scenario (van Vuuren et al. 2014, PBL 2023). The relation between economic development, defined as GDP (Gross Domestic Product, Purchasing Power Parity), and the status of sanitation and wastewater treatment, was used to define the level of sewerage connection and the level of treatment in the future (Van Puijenbroek, Beusen and Bouwman 2019, Van Puijenbroek et al. 2023). These scenarios were based on the population and economic developments in 200 countries.

In this study, five ambition levels were evaluated. The Business-as-usual ambition level (BAU) is the baseline and the low, moderate, high and max ambition levels are subsequent improvements of this baseline (PBL 2023). The BAU scenario for sanitation was based on the relation between economic growth and improvement of sanitation, in such a way that the global trend in sewerage connection between 2000 and 2015 was continued till 2070 (Figure 3). The BAU scenario for wastewater treatment was also based on this relation and parametrized to continue the current trend. The other types of sanitation were based on the relation between sanitation and wastewater treatment.

The Low ambition scenario was based on the economic development in the future to define sewer construction and wastewater treatment. Therefore, the GDP PPP of each country was used to calculate the sewer connection, septic tanks and pit latrines, the remaining part was assigned to unimproved sanitation. Also the level of wastewater treatment was based on the economic development of each country.

The Moderate ambition scenario was based on the Low ambition scenario but with higher investments in sewer and wastewater treatment, instead of reduction of the growth in sanitation as in BAU, extra investments were included for an opposite effect than BAU,

The High ambition scenario was based on the Moderate ambition scenario, whereby sanitation was equal to the Moderate ambition, but wastewater treatment was upgraded to at least secondary treatment in 2050. In practice, this was a slight difference. The major difference of this pathway compared with the Moderate ambition is a source-measure: the reduction of P in dish-washer and laundry washing detergents. Without environmental policy, these detergents have high content of phosphorus. With environmental policy, the content is nearly zero. In the EU, U.S., Australia, Singapore and some other countries, only P-free detergents are allowed. In this scenario, all detergents are P-free from 2050. With increasing prosperity, the use of detergents will increase, and therefore, this results in a serious amount of P emissions without environmental policy {Van Puijenbroek, 2018 #811}.

The Max ambition scenario was an unrealistic scenario for many countries in respect to wastewater treatment. In this scenarios, all cities have 100% sewerage connection and tertiary treatment in 2050.

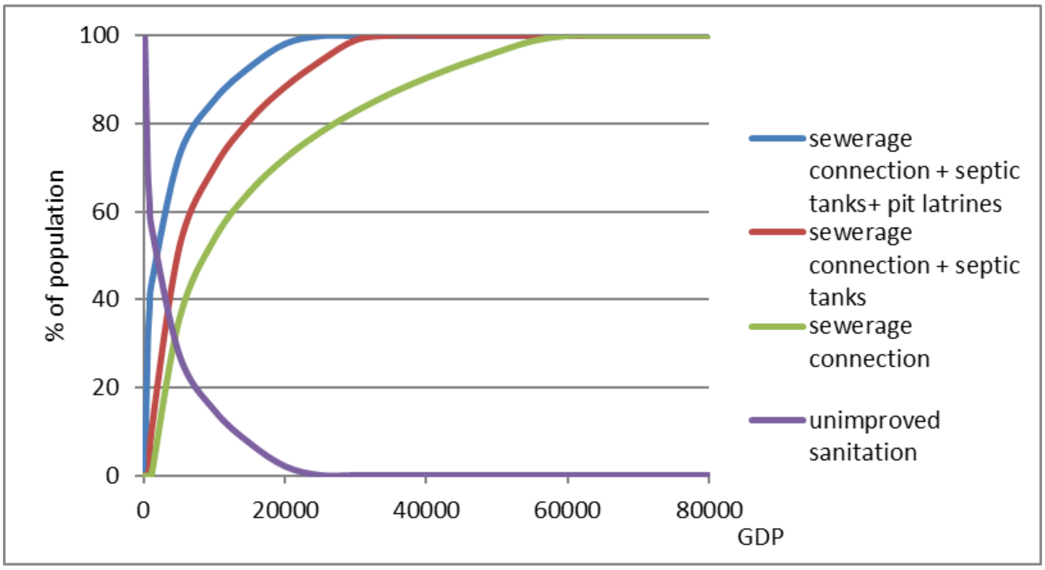
These scenarios are characterized as:

- this BAU scenario as 'continuation of current global trends';
- this Low ambition as 'economy driven development for sanitation and wastewater treatment';
- this Moderate ambition as 'with extra economic investment is a high level of sanitation and wastewater treatment in short time realized';
- this High ambition as 'with extra economic investment and extra policy to reduce emissions by source-measures;
- the Max ambition is an unrealistic, maximum level of sanitation and wastewater treatment.

2 The model

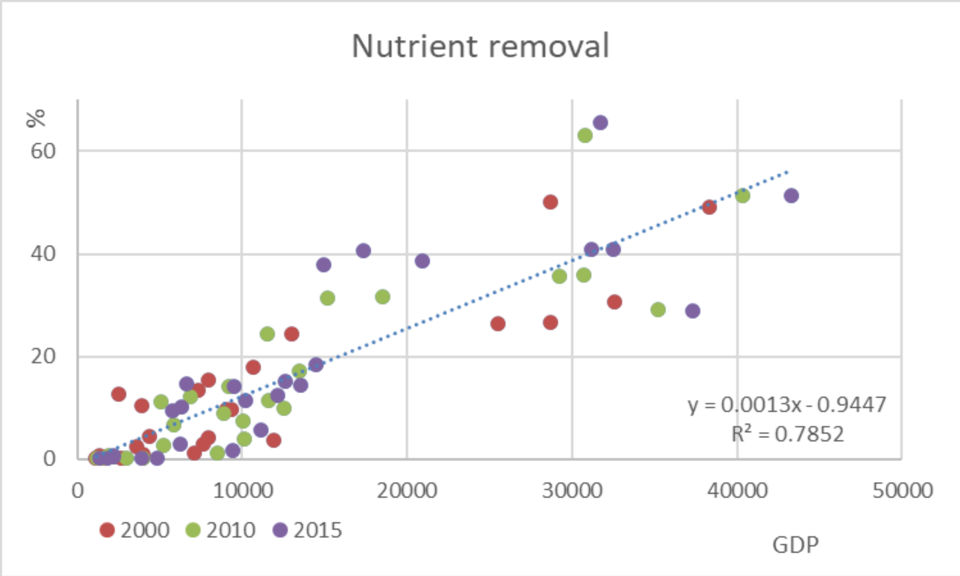
The sanitation and wastewater treatment scenarios are based on the method described in Van Puijenbroek et al. (2023). The existing model was extended with unimproved sanitation, pit latrines and septic tanks. First, the relation between GDP and sewer systems is used, next the percentage sewer connection and pit latrines are based on the relation with GDP, and finally the rest is used for unimproved sanitation. Wastewater treatments is also related to GDP based on Van Puijenbroek, Beusen and Bouwman (2019). This model is based on the four most important groups of sanitation: unimproved, pit latrines, septic tanks and sewer systems. On this level is global information on a country scale available (WHO and Unicef 2019).

Figure 1
The relationship between GDP and four types of sanitation. These relations are for SSP2 Low ambition. In the ambition SSP2-BAU the results for the first 3 lines are multiplied with a correction of 0.6, while in the medium and higher ambitions, this is multiplied by 1.3. The factor for BAU is chosen so that on a global scale, the straight line from 2000 till 2015 of the sewerage connection is continued in the future (see Figure 3). The factor of the medium and high ambitions is chosen as the opposite from BAU.



The pathogen emissions are simulated using the GloWPa model. A first version of this model for *Cryptosporididum* is described in Hofstra and Vermeulen (2016). The current version of the model uses the 13 sanitation categories from the Joint Monitoring Program (JMP) by WHO and UNICEF, including the different sewer, pit latrine and septic tank systems and open defecation practices. This version of the model is briefly described in Okaali et al. (2022). The model is used with the scenarios in this paper with some assumptions. The assumption is that within the pit latrine, septic tank and open defecation categories, the division over the categories is as in the present. Another assumption is that the disease incidence for *Cryptosporidium* is constant into the future. This is not realistic for a long term scenario, because with a different focus on healthcare or reduced emissions, the disease incidence can reduce. However, for the areas with the highest disease burden, the emissions likely increase and there the disease incidence could increase even further.

Figure 2
The relation between GDP and wastewater treatment, which is expressed as percentage nutrient removal. This relation is used for the Low Ambition. For the BAU ambition, the maximum nutrient removal is 80%, in the Low ambition 85% and in the higher ambitions 90%. See Van Puijenbroek et al. (2023) for more details.



The costs are based on investments costs (CAPEX) and yearly costs to maintain the sewerage systems and wastewater plants (OPEX). Both costs were different for urban and rural areas and specified for sewerage systems, primary, secondary, tertiary and quaternary wastewater treatment (Table 1) (Kind, Schenau and M. Bakker 2021).

For each country , the number of new inhabitants connected to sewerage systems and inhabitants with wastewater treatment were multiplied with the corresponding values. The costs were different for countries depending on their income whereby the next assumptions were used:

- High income countries with a GDP higher than 15000 US$/year had no correction factor;
- Upper middle income countries with a GDP between 7500 and 15000 US$/year had a correction factor of 0.75;
- Lower middle income countries with a GDP between 1500 and 7500 US$/year had a correction factor of 0.5;
- Low income countries with an GDP of less than 1500 US$/year had a correction factor of 0.25;

The results were aggregated to investment and annual costs. In this calculation, fixed prices were used for the whole period and countries are classified on their income based on the current situation. This is of course a very simple method whereby a future increase in prices is not included. Therefore, these results can only be seen as an indication of which costs are needed whereby investment and maintenance can be compared.

Table 1
Investment costs (CAPEX) and maintenance costs (OPEX) for high income countries based on the current situation (Kind, Schenau and M. Bakker 2021).

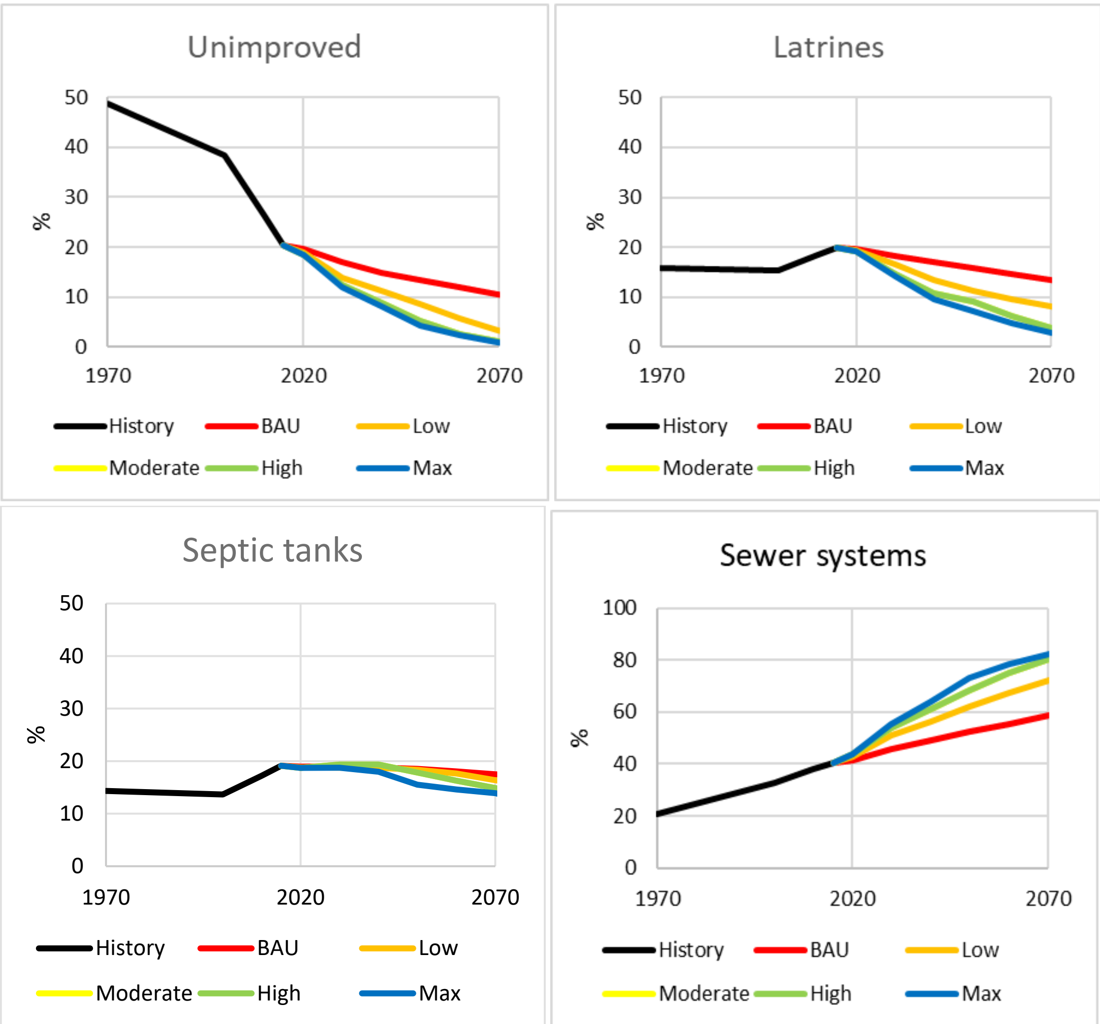
	Header	Investment US$/cap	Yearly maintenance costs US$/year, cap
Sewerage connection	rural	18000	313
	city	6000	104
Primary treatment	rural	563	75
	city	189	37
Secondary treatment	rural	2523	285
	city	686	96
Tertiary treatment	rural	4621	507
	city	1348	166
Quaternary treatment	rural	7011	755
	city	2116	246

3 Results

3.1 Results sanitation

Unimproved sanitation reduces slowly in the BAU scenario but unimproved sanitation is still the situation for 10% of the global population in 2070 (Figure 3, 4, 5 and Table 2). Pit latrines and septic tanks slowly reduces in the BAU but are still present in 2070; in the other ambition levels both sanitation types reduce more. The connection between sewer systems increases from 42% in 2020 to 58% in BAU in 2070 and 80% in the Moderate and High ambition scenario. In the Max scenario, this is only 2% more.

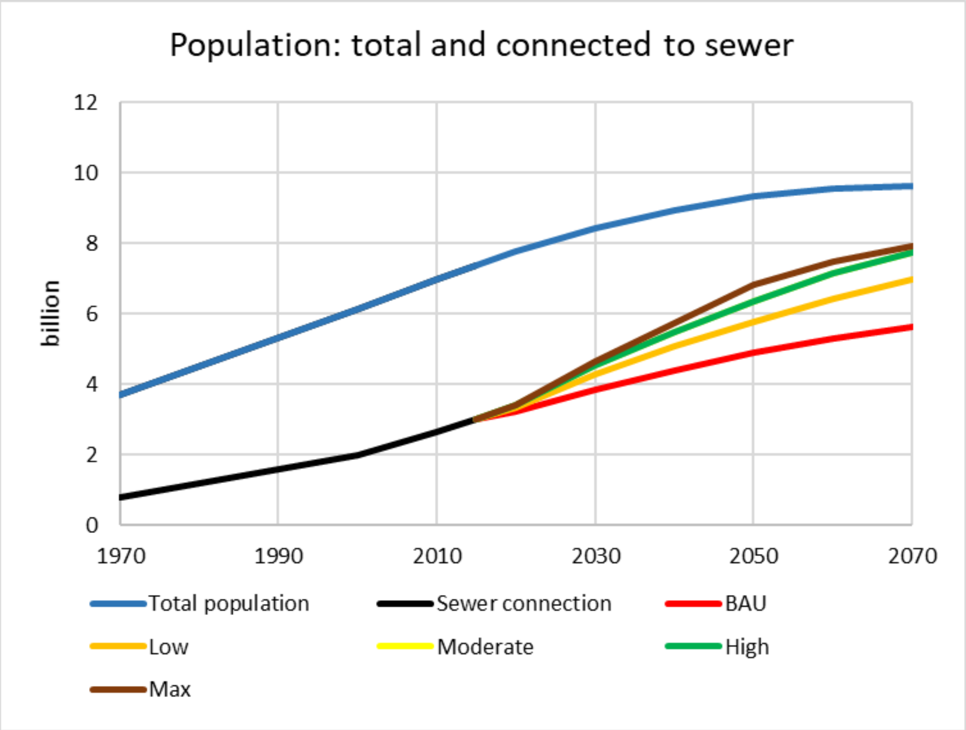
Figure 3
Development for sanitation in the BAU, Low, Moderate, High and Max scenario expressed as percentage of total population.



In absolute numbers, the number of people connected to a sewer system increases from 3.2 billion in 2020 to 5.6 billion in 2070 in the BAU scenario and reaches 6.3 billion in the High ambition scenario. The regional differences are very contrasting with hardly any improvement in Sub-Saharan Africa in BAU till 2050 and only little improvement in 2070 (Table 2).

Wastewater treatment improved from nearly nothing in 1970 till 14% in 2020 and will further improve till 28% in 2070 in BAU or with extra investments 51% in the High ambition. In the unrealistic Max ambition, this will further improve to 71% (Figure 4, 6, Table 2).

Figure 4
Total population and population connected to a sewer (above) and wastewater treatment expressed as global percentage nutrient removal



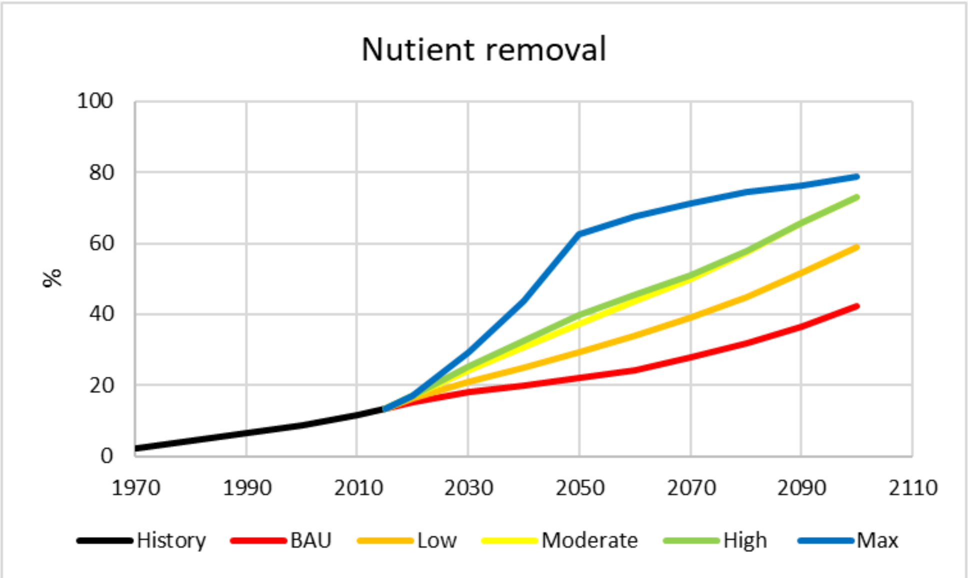


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Figure 5
Number of people classified according to sanitation types in 10 regions (see 6.1).

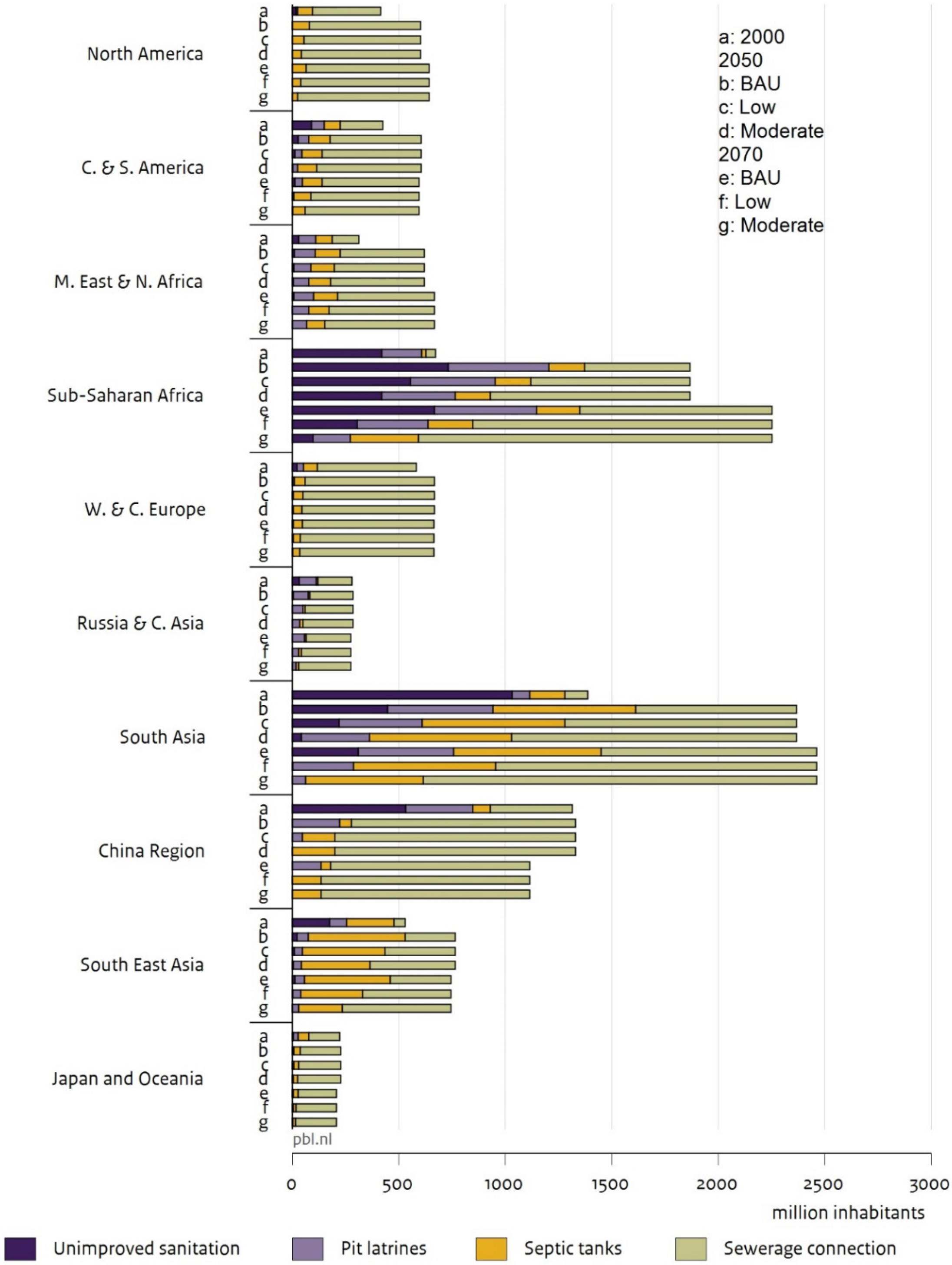


Figure 6
Types of wastewater treatment in 10 regions (see 6.1).

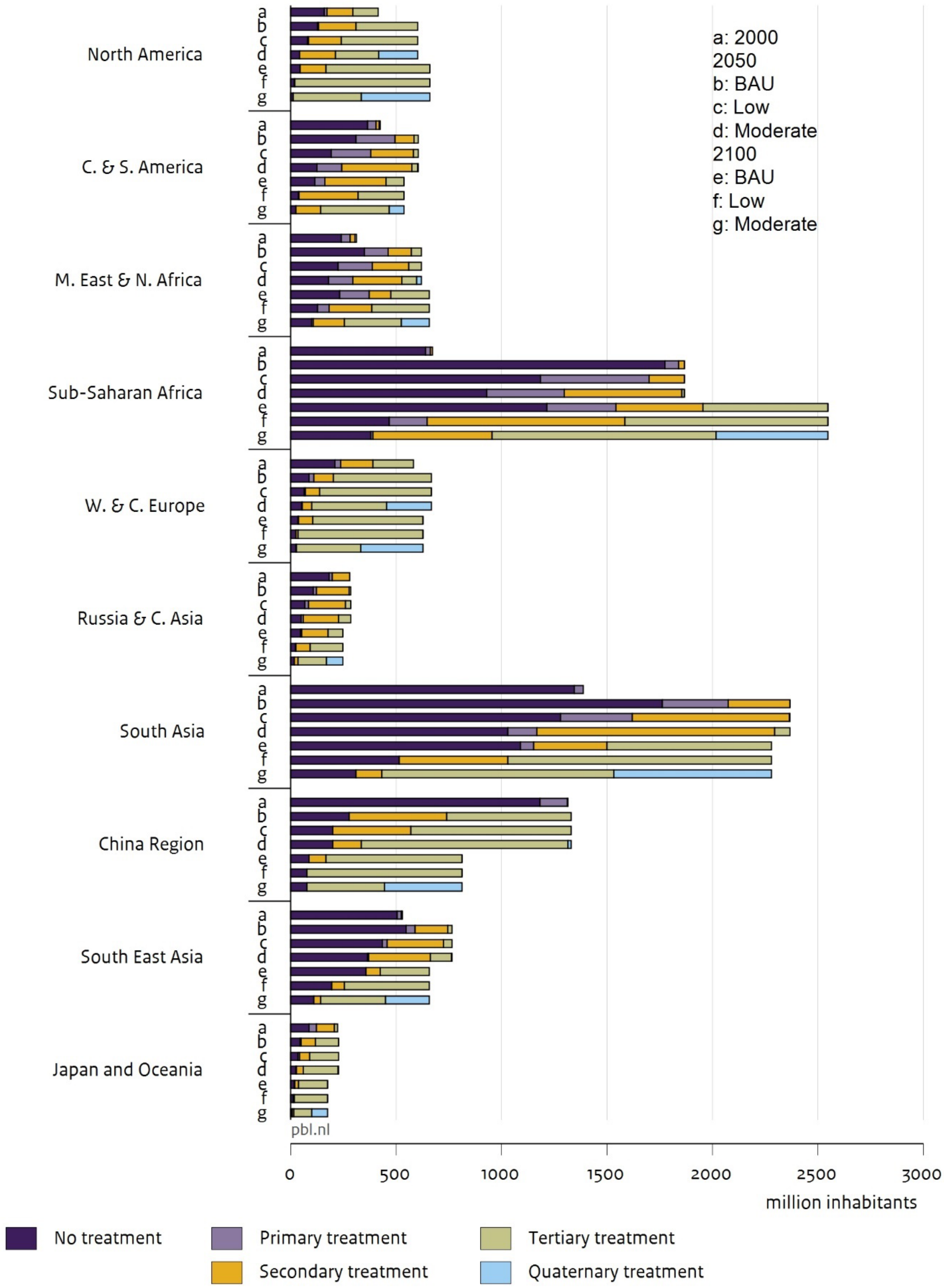


Table 2
The total number of people with connection to sewerage systems and having wastewater treatment expressed as nutrient removal.

			BAU		Low		Moderate		High		Max	
Connected to sewer (million)	**1970**	**2020**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**
North America	164	407	523	579	547	604	560	620	560	620	560	620
Central - and South America	60	319	426	456	464	508	489	535	489	535	549	556
Middle East and North Africa	33	244	396	455	424	494	440	516	440	516	525	591
Sub-Saharan Africa	15	91	497	901	749	1405	939	1660	939	1660	1165	1726
West and Central Europe	299	544	608	619	619	628	624	631	624	631	624	631
Russia and Central Asia	75	170	202	209	224	233	236	243	236	243	240	246
South Asia	21	256	757	1012	1089	1508	1339	1848	1339	1848	1343	1848
China Region	45	913	1052	935	1130	980	1130	980	1130	980	1130	980
South East Asia	4	92	234	286	329	416	401	511	401	511	486	537
Japan and Oceania	58	184	189	181	196	190	201	194	201	194	202	194
World	775	3220	4884	5633	5772	6966	6358	7738	6358	7738	6823	7929

With at least secondary			BAU		Low		Moderate		High		Max	
treatment (million)	**1970**	**2020**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**
North America	90	341	471	562	517	604	560	620	560	620	560	620
Central - and South America	0	69	110	209	224	402	361	534	478	535	549	556
Middle East and North Africa	0	87	158	229	234	339	326	462	440	516	525	591
Sub-Saharan Africa	0	17	28	205	168	742	570	1435	937	1658	1165	1726
West and Central Europe	51	482	559	595	599	622	613	631	615	631	624	631
Russia and Central Asia	0	107	162	185	200	224	225	242	236	243	240	246
South Asia	0	15	293	753	749	1319	1201	1831	1339	1848	1343	1848
China Region	0	816	1051	934	1130	980	1130	980	1130	980	1130	980
South East Asia	0	20	175	256	307	405	395	511	401	511	486	537
Japan and Oceania	0	152	175	169	184	184	199	193	200	194	202	194
World	141	2105	3183	4098	4312	5821	5578	7439	6335	7735	6823	7929

			BAU		Low		Moderate		High		Max	
(% nutrient removal)	**1970**	**2020**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**	**2050**	**2070**
North America	14	41	53	60	61	70	69	79	69	79	82	85
C. & S. America	0	8	12	20	20	33	28	45	34	45	77	79
M. East & North Africa	1	11	15	20	22	31	30	43	35	46	72	76
Sub-Saharan Africa	0	1	1	5	6	17	14	29	20	32	53	65
W. & C. Europe	6	58	65	70	72	77	78	84	78	84	83	85
Russia & C. Asia	0	16	25	31	33	44	41	57	42	57	72	76
South Asia	0	1	6	14	14	27	22	40	24	40	48	64
China Region	0	23	52	66	60	75	68	79	68	79	72	79
South East Asia	0	3	11	21	19	34	27	46	27	46	54	62
Japan and Oceania	2	38	53	64	60	73	68	81	68	81	76	83
World	2	15	22	28	29	39	37	50	40	51	63	71

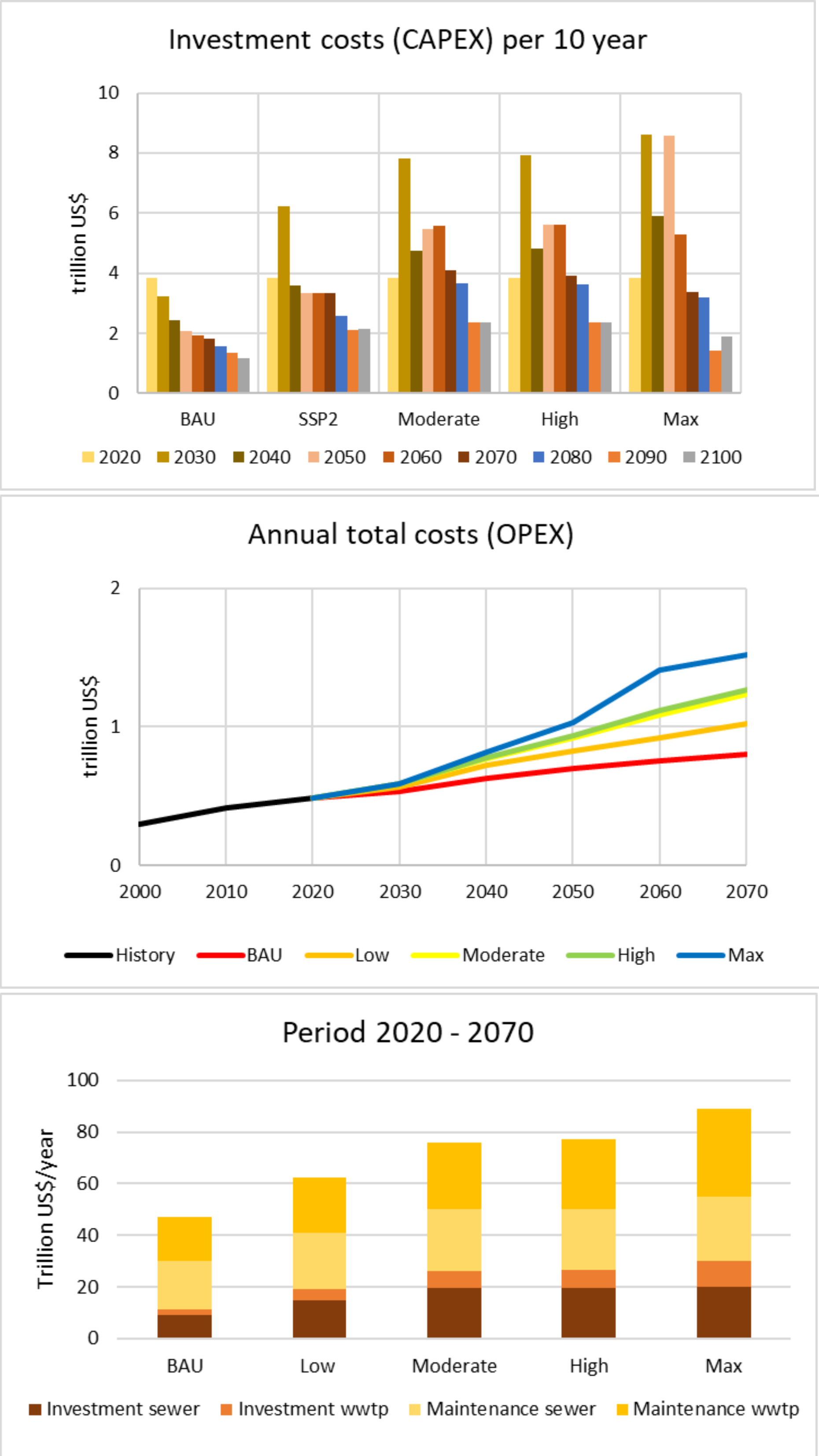
3.2 Results investments and yearly costs

Total investments costs depend on the new build sewer connected households and the new build capacity of wastewater treatment plants calculated per 10 years, while maintenance costs depend on the total number of sewer connections and wastewater treatment plants (Figure 7 and appendix 2). Although the total number of household connections is increasing, the growth of sewered connections, expressed as the number of new connected households per decade, decreased The total investments costs in the BAU and Low ambition is therefore decreasing in the first decades. This is also caused by the assumption that low income countries have lower costs, otherwise the investment and maintenance costs would be much higher and should increase each decade. The investment cost show different developments for the ambition levels. In the BAU ambition, this will decline from 4 trillion US$ in 2010 and will halve in 2050 and onwards. In the other ambitions this will further increase. In the Moderate and High Ambition, this will be between 5 and 6 trillion US$ in the period 2030 and 2060.

The yearly annual costs needed to maintain the underground infrastructure and wastewater treatment plants, will increase in all ambitions, the increase varied from 0.5 trillion US$ to 0.8 – 1.6 depending on the ambition. But with higher investments, also the maintenance costs further increase. About a quarter till a third of the total costs are investment costs, the main part are maintenance costs. Maintenance of sewer systems and wastewater treatment plants need to be included In future plans. Failing sewer systems, for example due to blockage caused by plastic waste, can result in unplanned discharge of the effluent. For example, in Zimbabwe, the not-functioning sewer system in the period 2008-2009 resulted in more than 4000 people killed by cholera (Mason 2009).

These results show that when investments in sewer systems and wastewater treatment are kept at the same level on a global scale, even the moderate ambition is realistic, although there is a great contrast between different regions. In most regions, the investment costs decline in the BAU ambition, but in Sub-Sahara Africa, a strong increase is needed to realize the small improvement of the BAU ambition. A special case is China, where the decline of the population in the second half of the century will need no extra capacity for sewer systems, but maintenance will be expensive for the declining population. These calculations are a first approach with assumptions with fixed costs, fixed categories of countries and standard unit costs.

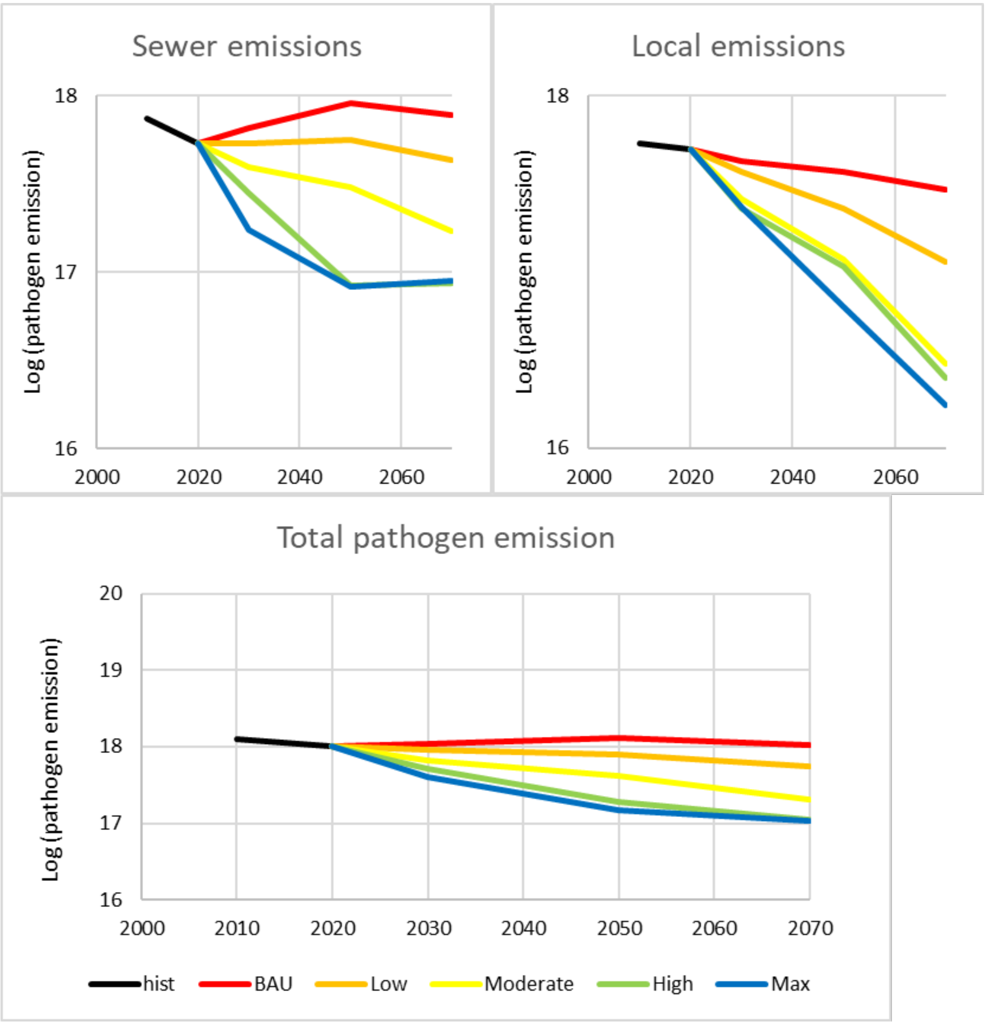
Figure 7
Investment costs (Capex) per 10 years and maintenance costs (Opex) per year for sewerage systems and wastewater treatment and total costs for period 2020-2070.



3.3 Results pathogen emissions

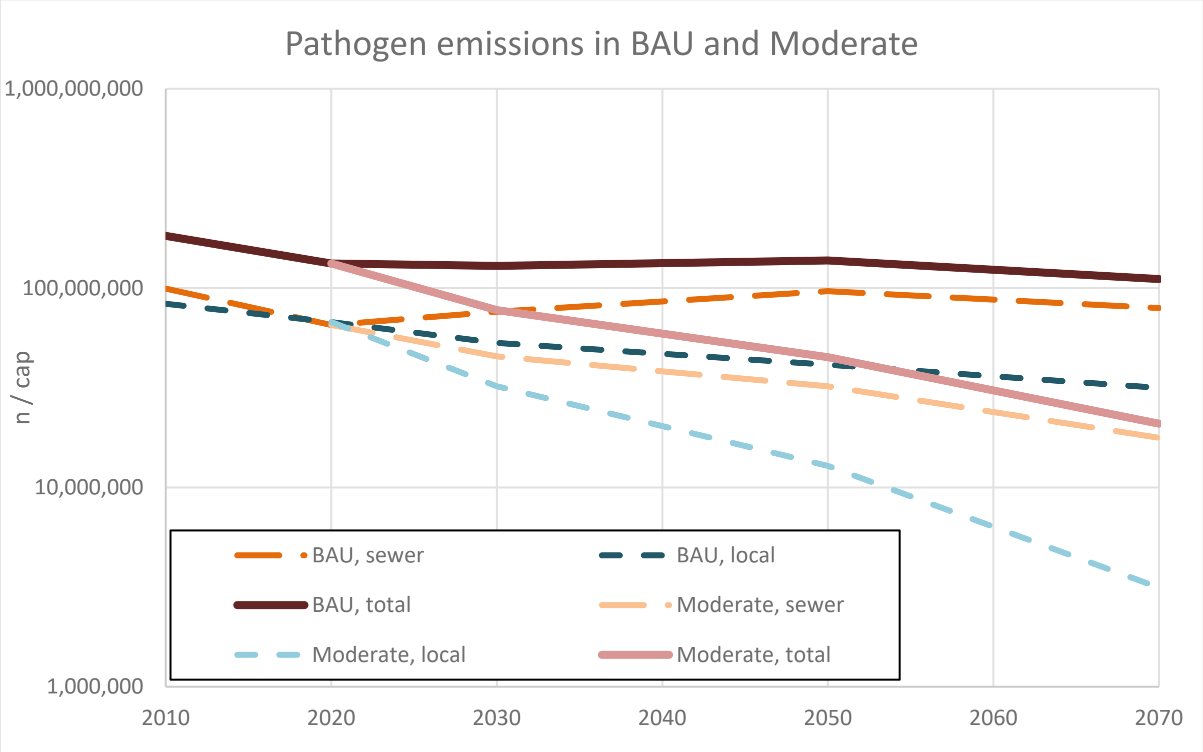
Emissions of the pathogens to surface waters are presented as total *Cryptosporidium* emissions and split in local emissions and emissions by sewer systems (Figure 8, 9 and total emissions for the 10 regions in Appendix 3). Local emissions are emissions from unimproved sanitation, pit latrines and septic tanks. These emissions are in the neighborhood of houses and are a risk to the local community. Sewer systems transport the waste away from the house, but the effluent can result in a high pathogen load to surface waters downstream. In many developing countries, the effluent is discharged without treatment, where the polluted water is a risk to the downstream community, or in case of use as irrigation water, to the farmers using that water.

Figure 8
Total emissions of Cryptosporidium and the emissions by sewer systems and local emissions.



Emissions are high in all of the scenarios. Even though reductions are visible for the Max scenario by 2070, remaining emissions from untreated sewage and unimproved sources make that emissions reduce by only 1-2 log units compared to 2010, and not further. Such 1-2 log unit reductions in emissions are small compared to possible improved reductions in treatment from primary (almost 0.5 log reduction) to quaternary (almost 4 log reduction).

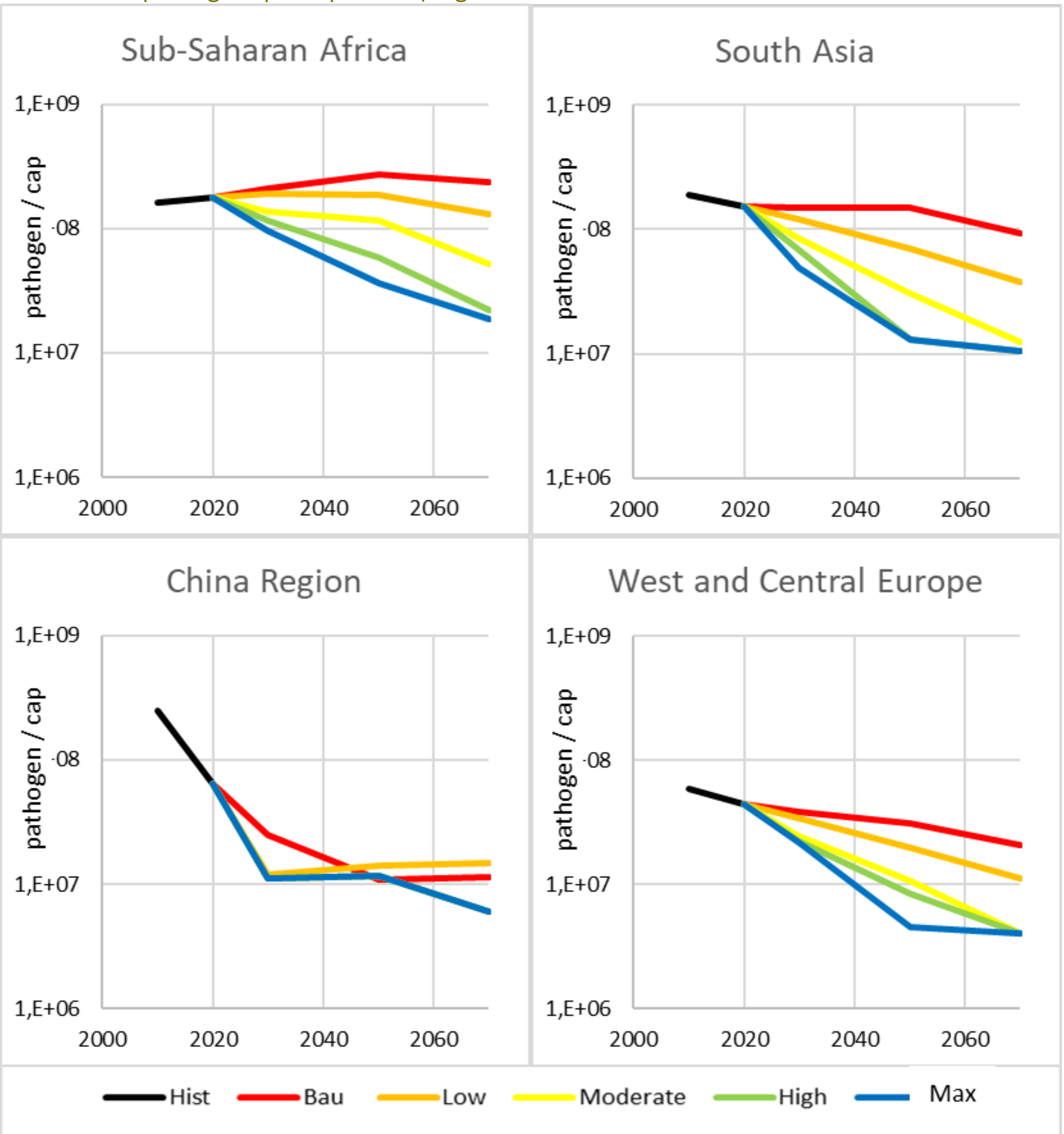
Figure 9
Total global emissions per capita for BAU and Moderate ambition for total emissions and split to sewer and local emissions.



The emissions of pathogens are still high in the BAU scenario as unimproved sanitation is still present in several regions. This means that human health is still threatened by local emissions in the neighborhood of houses in several regions even in 2070. Downstream emissions will be higher in many regions, as a result of untreated discharge of wastewater. This is especially a risk for use of water for irrigation, recreation or drinking water. As most irrigated agriculture is located downstream urban areas, the irrigated water polluted with human pathogens will be a risk for people working in irrigation systems (Thebo et al. 2017).

To demonstrate the differences per region, the results are presented as the number of pathogens per capita (Figure 9, 10). Per capita, the emissions increase in the BAU ambition in Sub-Saharan Africa, are stable in South Asia and further decrease in West and Central Europe. But also the numbers per capita are much higher in Sub-Saharan Africa and South Asia than in West and Central Europe. Total emissions increase in Middle East and North Africa, Sub-Sahara Africa and South Asia, due to an increase in sewer emissions without sufficient treatment. In Sub-Saharan Africa, also the local emissions increase.

Figure 10
Emissions of pathogens per capita for 4 regions.



3.4 Results nutrient emissions

Nutrient emissions will increase till 2070 with the same speed as in the period 1970-2020 for both nitrogen and phosphorus (Figure 11). In the BAU ambition, this will be 50% higher for nitrogen and 70% higher for phosphorus than in 2015. This global increase is a consequence of population growth, prosperity and building of sewerage systems without sufficient wastewater treatment. A reduction of the phosphorus emissions is possible in combination with source measures, e.g. the ban of phosphorus in detergents. For nitrogen, only in the unrealistic maximum ambition is a decrease in emissions possible, but this ambition is unrealistic. Even in the High Ambition increase the nutrient emissions increase due to the population growth, the increase in sewer connection without sufficient wastewater treatment.

But each region is different and therefor, global pictures are mistaken (Figure 12). In West and Central Europe, the emissions dropped as a result of improving wastewater treatment forced by the EU wastewater treatment act (EEC 1991) and policy to reduce emissions from laundry and dishwasher detergents (EU 2012), in combination with low population growth and high economic standard. Without extra environmental policy, these emissions will slowly increase with population growth.

The China region is characterized by high economic growth and the typical Chinese population growth, a slow growth till a maximum around 2030 and then a decreasing population size. The high economic growth makes investments in wastewater treatment possible.
In Sub-Saharan Africa and South Asia, emissions will increase rapidly to 4 to 7 times the current level. In the low and moderate scenario, the emissions can be higher than the BAU scenario. This is explained by more sewerage connections with lower wastewater treatment capacity.
In the High ambition scenario, the effect of source measures to reduce phosphorus emissions shows a major effect. Before policy measures forbid the use of phosphorus rich detergents in Europa, this was an important contribution to phosphorus emissions.

Figure 11
Global emissions of nitrogen and phosphorus to surface water.

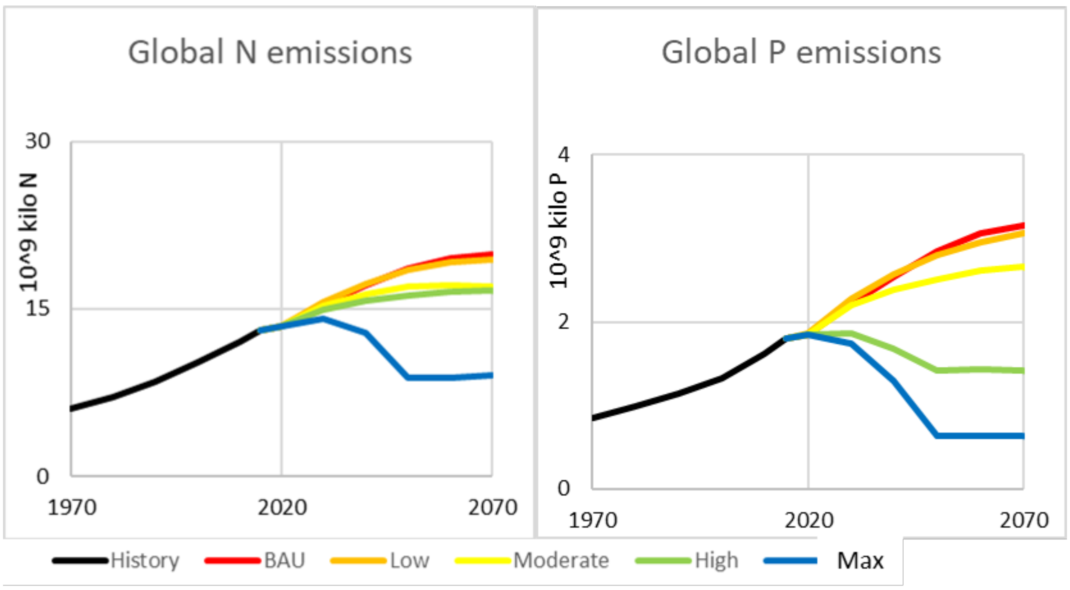
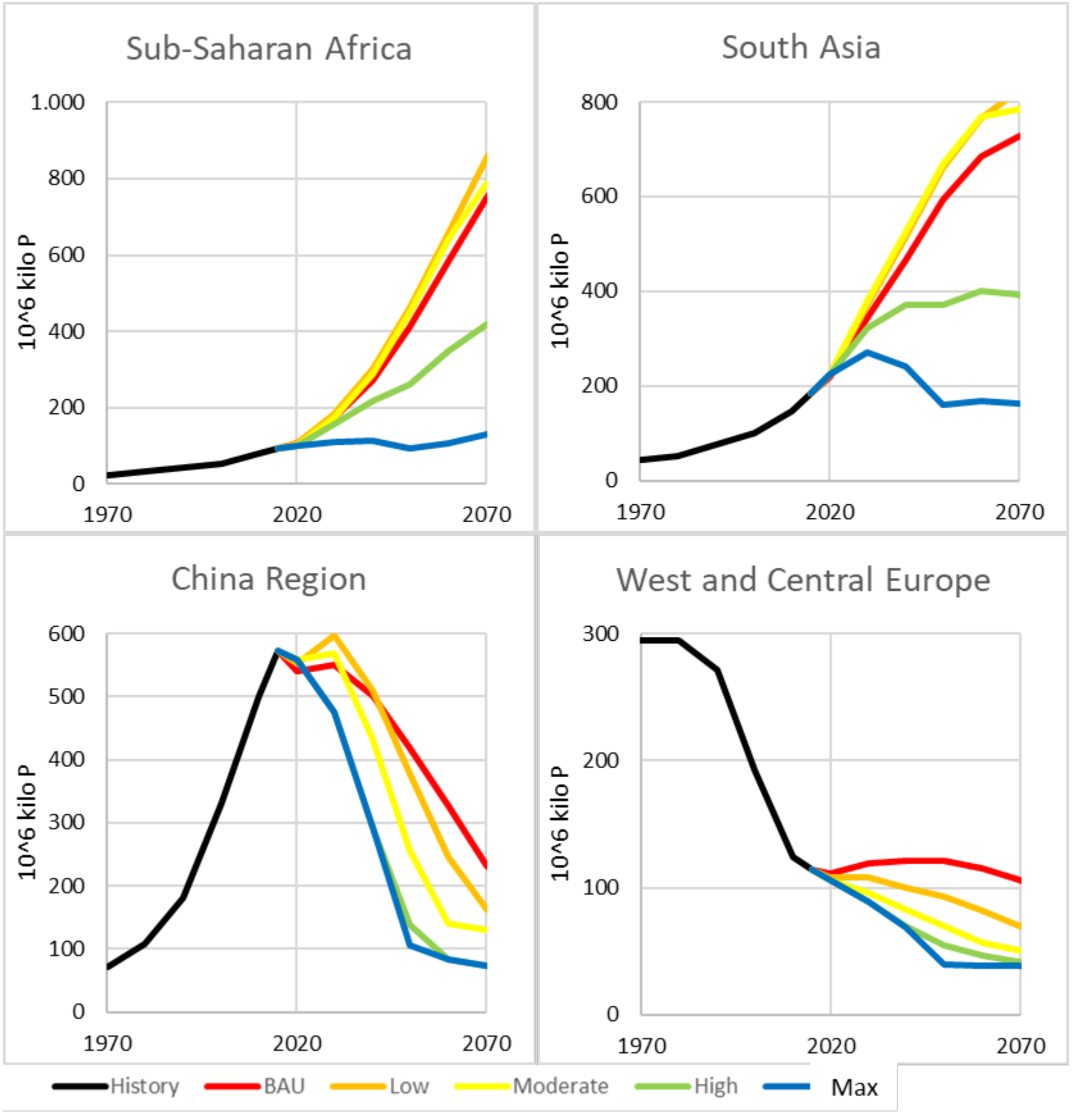


Figure 12
Phosphorus emissions to surface water in 4 regions.



3.5 Results SDG 6

The target to meet SDG 6.2 on sanitation will not be met in 2030, especially Sub-Saharan Africa will lag behind (Figure 13, Table 3). SDG 6.3 can be met in the High scenario in 2030, but in other scenarios it will be later (Table 4). In the BAU scenario this will not be met in 2070 in Central- and South America, Africa and Middle East. In all regions, there is progress till 2070, but the level is insufficient.

SDG 6.2 has a target to have improved sanitation for all and safely managed pit latrines, septic tanks and sewer effluent. Improved sanitation is an ambitious target, especially for Sub-Saharan Africa. The increase in prosperity is not enough to realize improved sanitation for all. Besides, the improvement in sanitation is not equally distributed between and within countries. Many countries did not show any improvement between 2000 and 2015: 16 countries had a relative increase in percentage unimproved, but taken into account the increase in population size, 44 countries had an absolute increase in number of people with unimproved sanitation. Therefore, an overall improvement in sanitation is not expected (Van Puijenbroek et al. 2023). Another aspect why SDG 6.2 is not met in e.g. Europe, is the management of pit latrines and septic tanks and untreated wastewater.

Table 3
Year when SDG 6.2 on sanitation could be met.

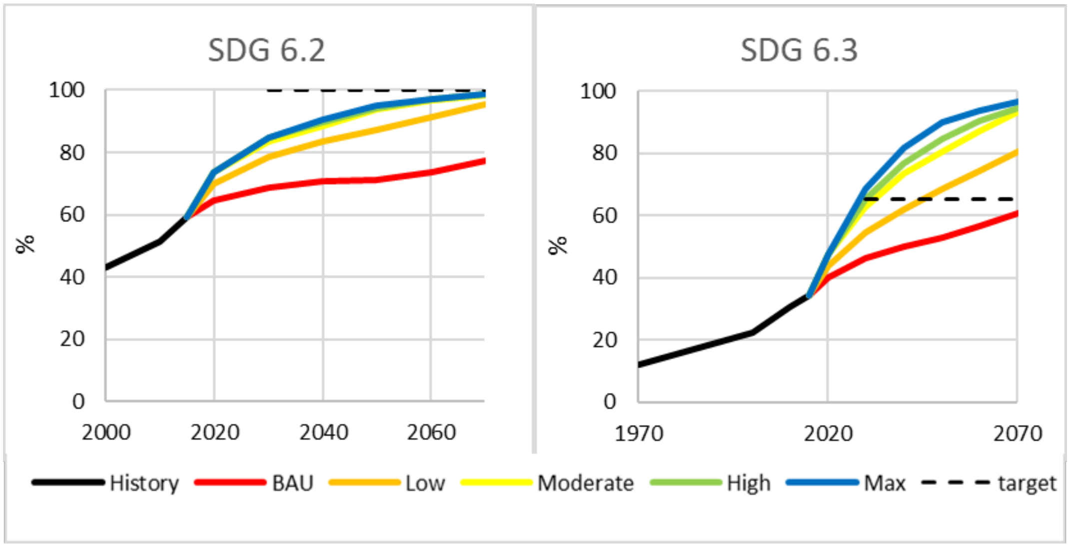
	BAU	Low	Moderate	High	Max
North America	>2070	2060	2050	2040	2040
Central - and South America	>2070	>2070	2060	2050	2050
Middle East and North Africa	>2070	>2070	2050	2050	2050
Sub-Saharan Africa	>2070	>2070	>2070	>2070	>2070
West and Central Europe	>2070	2070	2060	2050	2050
Russia and Central Asia	>2070	2070	2050	2040	2040
South Asia	>2070	2070	2060	2060	2060
China Region	2050	2030	2030	2030	2030
South East Asia	>2070	2070	2060	2050	2050
Japan and Oceania	>2070	>2070	2050	2050	2050
World	>2070	>2070	>2070	>2070	>2070

Table 4
Year when SDG 6.3 on wastewater treatment could be met.

	BAU	Low	Moderate	High	Max
North America	2050	2040	2030	2030	2030
Central - and South America	> 2070	2060	2040	2040	2030
Middle East and North Africa	> 2070	2040	2030	2030	2030
Sub-Saharan Africa	> 2070	2070	2060	2050	2050
West and Central Europe	2040	2030	2030	2030	2030
Russia and Central Asia	2060	2040	2040	2030	2030
South Asia	2070	2050	2040	2040	2040
China Region	2030	2020	2020	2020	2020
South East Asia	2050	2030	2030	2030	2030
Japan and Oceania	2030	2030	2030	2030	2030
World	> 2070	2050	2040	2030	2030

SDG 6.3 is less ambitious as it has to halve the level of untreated wastewater and with different targets for dry lands and coastal regions, whereby primary treatment is sometimes sufficient. Therefore, this target can be met earlier than SDG 6.2. Both SDG goals will not be met in 2030, but will improve till 2070. Especially China, with a very high economic growth has the opportunities to improve sanitation and wastewater while other regions lack behind.

Figure 13
SDG 6.2 and SDG 6.3 with their target for 2030.

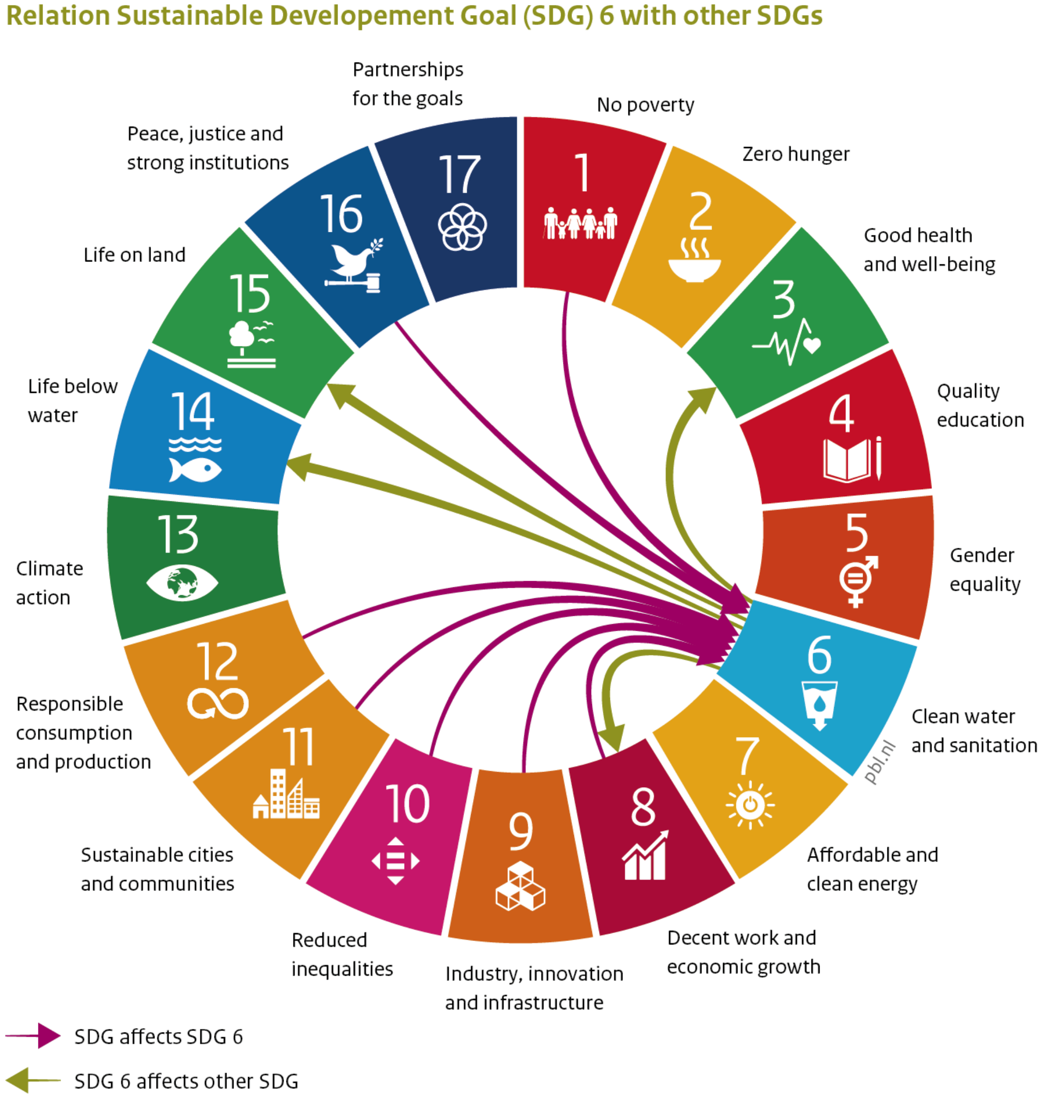


SDG 6 is related to several other SDGs (Wang et al. 2022). These relations can be divided in input relations, whereby reaching the SDG target has a positive effect on SDG 6 and output relations whereby the level of implementation of SDG 6 effects the other SDGs (Table 5, Figure 14). The most important SDGs that affect realization of SDG6 targets are SDG1 - end poverty, SDG9 – build resilient infrastructure, SDG10 – reduce inequality, SDG11 – make cities sustainable, SDDG12 – sustainable consumption. The SDGs that depend on realization of SDG6 are SDG3 – human health, SDG14 – life under water, SDG15 – protect ecosystems. SDG8, sustainable economy, has both input and output relations with SDG6. Other SDGs are less direct, such as SDG7 for energy efficiency or SDG2 for zero hunger, or not at all related with SDG6.

Table 5
SDG 6 in relation to other SDG targets.

SDG	Target	I/O	
1	End poverty in all its forms everywhere.	I	Poverty is a basic factor determining the development of SDG6.
3	Ensure healthy lives and promote well-being for all at all ages.	O	This SDG is strongly affected by SDG 6 as waterborne diseases are included in SDG 3.3
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.	I/O	Economic growth is a key factor to improve SDG 6 and therefor determines SDG 6. Tourism is included in SDG 8, which can be negatively affected by insufficient water quality and is therefore related to SDG 6.
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.	I	Sewerage systems are the underground infrastructure of cities. Also the availability of knowledge and technology are necessary for building wastewater treatment plants
10	Reduce inequality within and among countries.	I	Sewer systems and wastewater treatment are unequally available between and within countries.
11	Make cities and human settlements inclusive, safe, resilient and sustainable.	I	Access for all to adequate, safe and affordable housing and basic services and upgrading slums is an essential aspect to sanitation
12	Ensure sustainable consumption and production patterns.	I	Reducing food waste and chemical waste results in less waste production
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development.	O	The emissions of human wastewater is a very important factor determining the ecology of seas and oceans.
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.	O	Aquatic ecosystems is include in 15.1. Human wastewater is a key factor for freshwater ecosystems and without sufficient management responsible for oxygen depletion and eutrophication. With unsafe drinking water, water has to be cooked before consumption. In a major part of the world, this is done with a wood fire, resulting in deforestation and degradation of terrestrial ecosystems.
16	Peace, justice and strong institutions	I	Reduce corruption, 16.5, and develop effective institutions, 16.6, international cooperation, 16.15a are key elements for an effective water management

Figure 14
SDG 6 related to other SDG’s, whereby reaching the goal of SDG 6 depends on other SDG’s (input) or the results of SDG 6 affects the SDG goals (output)



Source: PBL

4 Conclusions

Sanitation, wastewater and finance

- Unimproved sanitation will slowly reduce but in the BAU scenario still 1 billion people will not have improved sanitation by 2070.
- The percentage of people with sewer connection slowly increases from 3 billion people (14% of global population) to 5.6 billion in 2070 in the BAU scenario, this will further increase to 7.7 billion in the moderate scenario.
- The level of wastewater treatment increases from 15% nutrient removal in 2020 till 28% in 2070 in BAU, this will increase till 39% in Low Ambition, 50% in Moderate ambition and 51% in High Ambition, in the unrealistic Max ambition, this will further increase till 71%.
- Emission of pathogens will locally decrease as a result of reduction of unimproved sanitation, but downstream the emissions will increase.
- Wastewater treatment will only slightly reduce the emission of pathogens in the sewer effluent, only with advanced quaternary treatment a serious reduction of the pathogens in sewer effluent is possible.
- Pathogen emissions will increase in Africa and South Asia and are much higher than in developed countries.
- Especially Sub-Saharan Africa will lag behind with 1% nutrient removal in BAU in 2070, an increase in pathogen emissions and a high increase of nutrient emissions.
- The total costs of investment and maintenance of wastewater treatment will be 47 trillion US$ in the period 2021-2070 in the BAU scenario; for the low and moderate scenario an extra of respectively 15 and 29 trillion US$ will be needed.

Emissions

- Pathogen emissions in the neighborhood of settlements will reduce with the increase in sewer systems, but these emissions will increase downstream with the sewer effluent.
- Nutrient emissions will increase by 50% for nitrogen and 70% for phosphorus in the BAU in 2070.
- Regional differences are contrasting, a strong decrease of emissions in China, a stable level in Western and Central Europe and a strong increase of 4 times in South Asia till 7 times in Sub-Saharan Africa.
- Source measures to ban the use of phosphorus in detergents are very effective.

SDGs

- SDG target 6.2.1 on sanitation will not be met in 2030, even in High ambition scenario this will only happen after 2070. Sub-Saharan Africa will not meet this target in 2070.
- SDG target 6.3 on wastewater treatment will not be met in 2070 in the BAU ambition, but in the High Ambition this is possible in 2030 on a global scale. On a regional scale, Sub-Saharan Africa and South Asia lag behind and in 2050 they will meet the target.
- SDG 6.3 is less ambitious as the target is to halve untreated wastewater and with lower targets for drylands and coastal areas, compared with SDG 6.2 whereby the target is to have improved sanitation for all.

Overall conclusion

- Sanitation and wastewater treatment are very important for global water quality and human health, negative effects can be avoided with expensive investments in sewer systems and wastewater treatment

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Appendix

Regions of the world

Figure 15
IMAGE regions: 1 Canada, 2 United States, 3 Mexico, 4 Rest of Central America, 5 Brazil, 6 Rest of South America, 7 Northern Africa, 8 Western Africa, 9 Eastern Africa, 10 South Africa, 11 OECD Europe, 12 Eastern Europe, 13 Turkey, 14 Ukraine +, 15 Asia-Stan, 16 Russia +, 17 Middle East, 18 India, 19 Korea, 20 China +, 21 Southeast Asia, 22 Indonesia +, 23 Japan, 24 Oceania, 25 Rest of S. Asia, 26 Rest of S. Africa, 27 Greenland. These regions are used for analysis.

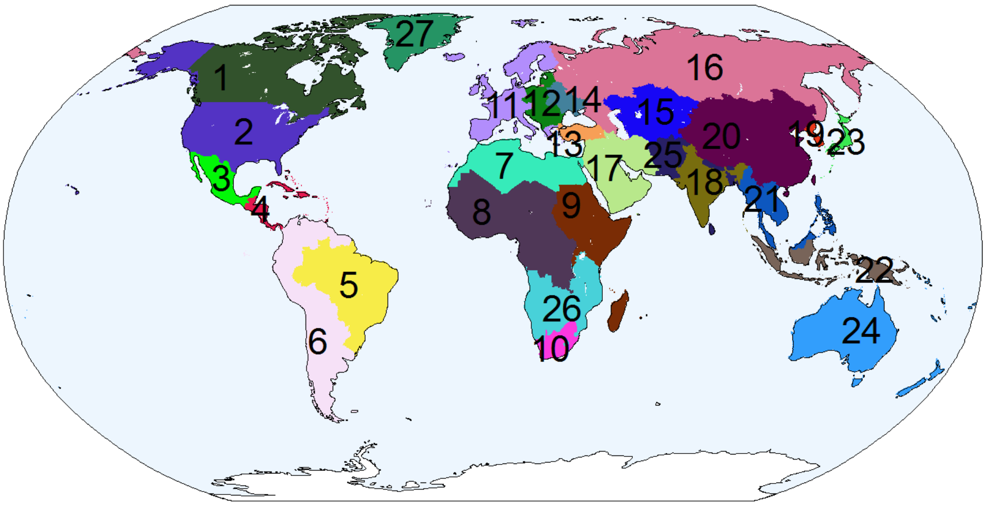
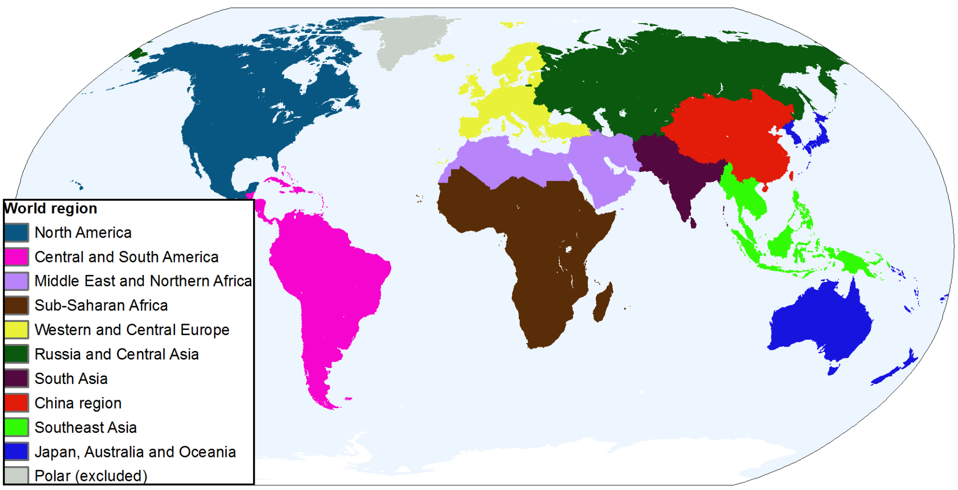


Figure 16
Definition of the 10 world regions used for presenting results.



CAPEX and OPEX costs in period 2020-2070

Trillion US$	**OPEX sewerage systems**					**CAPEX sewerage systems**				
region	**BAU**	**Low**	**Mod.**	**High**	**Best**	**BAU**	**Low**	**Mod.**	**High**	**Best**
North America	2.45	2.57	2.67	2.67	2.67	1.00	1.20	1.44	1.44	1.44
C. & S. America	1.59	1.73	1.82	1.82	1.95	0.62	0.93	1.08	1.08	1.21
M. East & N. Africa	1.25	1.35	1.41	1.41	1.59	0.80	1.00	1.10	1.10	1.39
Sub-Saharan Africa	0.94	1.44	1.91	1.91	2.19	1.80	3.36	4.47	4.47	4.68
W. & C. Europe	3.50	3.59	3.64	3.64	3.64	0.68	0.81	0.88	0.88	0.88
Russia & C. Asia	0.73	0.84	0.90	0.90	0.91	0.19	0.39	0.48	0.48	0.49
South Asia	1.72	2.48	3.46	3.46	3.46	2.24	3.84	6.39	6.39	6.39
China Region	4.96	5.90	5.97	5.97	5.97	1.01	2.09	1.96	1.96	1.96
South East Asia	0.64	0.87	1.05	1.05	1.18	0.65	1.06	1.43	1.43	1.52
Japan and Oceania	0.97	1.03	1.08	1.08	1.08	0.14	0.18	0.23	0.23	0.23
World	18.7	21.8	23.9	23.9	24.6	9.12	14.85	19.45	19.45	20.18
Extra costs (+BAU)		3.05	5.15	5.15	5.90		5.73	10.33	10.33	11.05

Trillion US$	OPEX wastewater treatment					CAPEX wastewater treatment				
region	BAU	Low	Mod.	High	Best	BAU	Low	Mod.	High	Best
North America	3.02	3.35	3.97	4.00	4.24	0.32	0.45	0.90	0.90	0.99
C. & S. America	0.69	1.03	1.37	1.56	2.52	0.12	0.22	0.36	0.37	0.72
M. East & N. Africa	0.77	1.02	1.29	1.43	2.12	0.12	0.22	0.36	0.39	0.63
Sub-Saharan Africa	0.23	0.76	1.34	1.71	3.36	0.09	0.27	0.52	0.61	1.20
W. & C. Europe	4.25	4.86	5.25	5.26	5.42	0.20	0.40	0.78	0.78	0.85
Russia & C. Asia	0.56	0.71	0.82	0.85	1.13	0.06	0.13	0.17	0.18	0.31
South Asia	0.94	1.86	2.73	2.97	5.08	0.30	0.57	0.88	0.90	1.91
China Region	4.90	5.93	6.57	6.57	6.98	0.85	1.47	2.07	2.07	2.54
South East Asia	0.54	0.83	1.14	1.16	1.70	0.17	0.25	0.39	0.39	0.51
Japan and Oceania	1.13	1.25	1.41	1.41	1.48	0.14	0.20	0.35	0.35	0.41
World	17.0	21.6	25.9	26.9	34.0	2.37	4.18	6.78	6.93	10.1
Extra costs (+BAU)		4.57	8.86	9.88	17.0		1.81	4.41	4.56	7.70

Trillion US$	OPEX wastewater treatment + sewer					CAPEX				
region	BAU	Low	Mod.	High	Best	BAU	Low	Mod.	High	Best
North America	5.47	5.92	6.65	6.67	6.92	1.32	1.65	2.33	2.33	2.43
C. & S. America	2.27	2.76	3.19	3.38	4.46	0.74	1.15	1.45	1.45	1.93
M. East & N. Africa	2.02	2.36	2.70	2.84	3.72	0.92	1.22	1.46	1.49	2.02
Sub-Saharan Africa	1.17	2.20	3.25	3.62	5.55	1.89	3.63	4.99	5.08	5.87
W. & C. Europe	7.75	8.45	8.88	8.89	9.06	0.88	1.21	1.66	1.66	1.73
Russia & C. Asia	1.29	1.55	1.72	1.75	2.05	0.25	0.52	0.65	0.66	0.80
South Asia	2.66	4.33	6.19	6.43	8.54	2.54	4.41	7.27	7.29	8.29
China Region	9.87	11.8	12.5	12.5	13.0	1.86	3.55	4.03	4.03	4.50
South East Asia	1.17	1.70	2.19	2.21	2.88	0.82	1.31	1.81	1.81	2.03
Japan and Oceania	2.10	2.29	2.48	2.49	2.56	0.28	0.38	0.58	0.58	0.64
World	35.8	43.4	49.8	50.8	58.7	11.5	19.0	26.2	26.4	30.2
Extra costs (+BAU)		7.6	14.0	15.0	22.9		7.5	14.7	14.9	18.7

Pathogen emissions of *Crytosporidium*

Emissions per region by local emissions, downstream by sewer systems and total emissions.

	Local			Sewer			Total		
10^15 pathogens	2020	2050	2070	2020	2050	2070	2020	2050	2070
North America	2,1			43,2			45,4		
BAU		0,3	0,3		38,9	15,3		39,2	15,7
Low		0,8	0,6		23,9	5,3		24,8	5,9
Moderate		0,0	0,0		3,7	0,0		3,7	0,0
Central - and South America	28,6			137,4			166,0		
BAU		13,3	6,9		139,3	103,1		152,6	110,0
Low		9,0	2,9		89,8	43,3		98,8	46,2
Moderate		0,0	0,4		45,5	6,9		45,5	7,3
Middle East and North Africa	14,2			83,0			97,2		
BAU		6,0	4,9		122,8	107,8		128,9	112,7
Low		5,8	4,1		70,7	54,3		76,4	58,3
Moderate		1,2	0,6		38,0	21,7		39,2	22,3
Sub-Saharan Africa	160,8			38,5			199,3		
BAU		197,5	170,1		310,5	358,5		507,9	528,6
Low		144,9	76,0		205,6	217,4		350,5	293,3
Moderate		98,1	28,5		118,4	88,1		216,5	116,6
West and Central Europe	2,3			25,2			27,5		
BAU		0,6	0,3		19,9	13,5		20,5	13,8
Low		0,7	0,4		12,6	7,1		13,3	7,5
Moderate		0,0	0,0		7,2	2,7		7,2	2,7
Russia and Central Asia	6,9			26,7			33,6		
BAU		1,7	0,2		20,3	13,1		22,0	13,3
Low		0,3	0,2		11,9	5,0		12,1	5,2
Moderate		0,0	0,0		5,4	2,8		5,4	2,8
South Asia	199,8			84,9			284,7		
BAU		151,4	111,4		203,1	119,0		354,5	230,4
Low		54,1	17,5		111,7	74,5		165,8	92,0
Moderate		13,9	0,0		57,8	30,5		71,7	30,5
China Region	53,7			40,0			93,7		
BAU		0,0	0,0		14,4	12,8		14,5	12,8
Low		3,5	3,0		15,5	13,4		19,0	16,5
Moderate		0,0	0,0		15,5	15,8		15,5	15,8
South East Asia	54,8			19,5			74,3		
BAU		14,3	10,1		25,9	16,7		40,2	26,8
Low		15,4	9,9		10,5	8,5		25,9	18,4
Moderate		3,8	0,7		7,0	6,4		10,8	7,1
Japan and Oceania	0,8			7,7			8,5		
BAU		0,3	0,2		6,4	5,7		6,8	5,9
Low		0,5	0,2		5,9	5,0		6,4	5,2
Moderate		0,0	0,0		2,2	1,0		2,2	1,0

Total	523,8			506,3			1030,1		
BAU		385,4	304,4		901,5	765,5		1286,9	1069,9
Low		234,8	114,7		558,1	433,7		792,9	548,4
Moderate		119,8	30,2		300,6	170,9		420,4	201,1