GLOBAL WATER PATHOGEN PROJECT
PART FIVE. CASE STUDIES

MAPPING PATHOGEN EMISSIONS TO SURFACE WATER USING A GLOBAL MODEL WITH SCENARIO ANALYSIS

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Summary

Highlights

- We supplement sparse pathogen data availability by mapping at a global scale
- We simulate pathogen emissions to surface water to improve spatial pattern understanding
- We analyse changes in emissions using sanitation management scenarios
- Installing sewerage without treatment leads to increased emissions
- Models with scenario analysis can support sanitation planning strategies

Graphical abstract

(Image produced by authors. Source of the computer image: [https://commons.wikimedia.org/wiki/File:Blue_computer_ic on.svg](https://commons.wikimedia.org/wiki/File:Blue_computer_ic_on.svg), source of bottom left map: Kiulia *et al.*, 2015)

Management objective

Diarrhoeal disease still is the fourth leading cause of death in children younger than 5 years of age and rotavirus is the main contributor to the diarrhoeal disease incidence. Faeces can contain rotavirus particles and these can spread to the environment and pose a public health threat through

sanitation systems. This case study demonstrates the opportunity of using (global) models together with scenario analysis to support sanitation safety planning and decision-making. In the case study we use a Global Waterborne Pathogen model for rotavirus emissions to surface water (GloWPa-Rota) to evaluate the effect of alternative sanitation strategies to control the waterborne spread of rotavirus. Policy-makers can use this information to select the most effective sanitation strategy.

Description

The GloWPa-Rota model calculates rotavirus emissions from human faeces to the surface water. Input variables comprise population numbers, population excretion rates of rotavirus, sanitation systems used (e.g. sewers, septic tanks, pit latrines, open defecation) and rotavirus removal in waste water treatment systems. Two scenarios have been assessed with the model. In Scenario 1 worldwide sewers, but not sewage treatment, were installed to replace open defecation, pit latrines and septic tanks, and no improvements to existing sewage treatment systems was made. Scenario 2 is the same as Scenario 1, but now with tertiary treatment added. These scenarios are unrealistic and undesirable, but serve the purpose of demonstrating the opportunities of using models with scenario analysis.

Outcome and recommendations

Figure 1 provides the case study results. This figure shows high emissions in densely populated parts of the world, particularly in developing countries or countries in transition (India, China, Nigeria, coast of Latin America). Emissions are a lot higher in Scenario 1, in particular in China, India, Sub-Sahara Africa and Latin America, but even in Europe. Emissions are reduced in Scenario 2. This shows that a campaign under the Sustainable Development Goals to end open defaecation by connecting people to sewers without sufficient sewage treatment would lead to a very significant increase in rotavirus emissions to surface water and put water users at increased health risk.

Figure 1. Rotavirus emissions (left) baseline (approximately the year 2010, top) and future (everyone a sewer, middle and everyone a sewer and tertiary treatment, bottom) and the difference between the future and baseline (right). The top left map is reproduced from Kiulia et al., 2015

Modelling with scenarios provides opportunities to support safe sanitation planning. Practitioners can use the results of this type of mapping studies to evaluate

emissions and management options in their own country. Moreover, they can compare their own country to other countries around them and learn from differences.

The model allows for other scenarios to be evaluated, such as global environmental change scenarios and scenarios that study what needs to be done to achieve the Sustainable Development Goals. In this case study the focus is on emissions to surface waters. Similar mapping approaches can be used for smaller study areas, such as countries and river catchments, and more specific scenarios. Scenario analysis could also be applied using a framework that couples emissions to concentrations in surface water and health risk.

Problem formulation

Diarrhoea is a very common disease worldwide and still is the fourth leading cause of death in children younger than 5 years of age (United Nations Inter-agency Group for Child Mortality Estimation, 2015). The disease burden is largest in developing countries (Bartram and Cairncross, 2010). Sanitation is important for the disease burden (Bartram and Cairncross, 2010; Hunter et al., 2010). Faeces can contain waterborne pathogens that deteriorate surface water quality and can infect people via the faecal-oral route, for example through intake of contaminated water during drinking, washing clothes, doing dishes, recreation, or eating fresh or processed food. However, currently we are unable to quantify the link between sanitation and health (Schmidt, 2014; Mills et al., 2018; WHO, 2018). We do not know how many pathogens from the faeces of infected humans and animals reach the water and infect humans. We also do not have spatially and temporally continuous microbial water quality monitoring data; pathogenic water quality data are sparse throughout the world. And even when we have observational microbial water quality data, we often cannot link the microbial water quality problems back to the source.

The microbial water quality can deteriorate and related diarrhoeal disease burden can increase due to socioeconomic development and environmental change (Levy et al., 2018; Sellers and Ebi, 2018). For example, an increased urban population and an urban sewage system that does not keep up with the growth, could deteriorate the surface water quality. In addition, high precipitation events and draughts, that are expected to increase due to climate change, influence the microbial water quality. High precipitation events can wash sewage onto the streets and into the houses, where the population is strongly exposed. During droughts, sewage can constitute up to 100% of the stream flow, creating a risk when the water is used for domestic purposes, such as washing. The impacts of such changes are still poorly quantified (Hofstra, 2011; Smith et al., 2014). The microbial water quality and possible changes should be taken into account in sanitation planning.

The disease burden can be reduced by management interventions (Bartram and Cairncross, 2010), such as waste and drinking water treatment. At present, the health impacts of sanitation improvements have been debated in

the literature (Moraes et al., 2003; Clasen et al., 2014; Patil et al., 2015; Sclar et al., 2016) and remain unclear (Mills et al., 2018; WHO, 2018). Therefore, the comparison and prioritisation of management interventions is currently difficult (Mills et al., 2018). Sanitation planners require more information on the microbial water quality and related disease burden to make sound decisions on the interventions to be implemented.

The UN agreed in the Sustainable Development Goals (SDGs) to improve health (SDG3), drinking water access (SDG6.1), sanitation (SDG6.2) and ambient water quality (SDG6.3.2) (United Nations General Assembly, 2015). To make these improvements and understand the linkages between the SDGs, a better understanding of the causal pathways that link sanitation and health through water is essential.

In this case study we present an approach that can help planners and decision makers to better understand their system and to prioritise management interventions. We have developed a mapping approach and apply in scenario analysis to simulate areas of highest concern and possible future changes.

Modelling enables quantification of the link between sanitation, the microbial water quality and human health. Data are available for many of the underlying drivers of the system. For example, data on population are available, just like information on the sanitation systems that are used, the removal of pathogens in wastewater treatment and persistence in the environment. Models can help to estimate environmental pathogen loading (how many pathogens reach the environment, or the water), their concentration (the pathogenic water quality) and the health risk and disease burden related to exposure (Hofstra et al., 2019). Models produce results that are spatially continuous, which enables identification of areas with high concentrations, the so-called hotspots. Moreover, models produce results for areas without data. Of course, models are simplifications of reality and they are therefore inherently uncertain. Evaluation of model results is therefore essential to determine their value for use in planning. Models can be developed at many different spatial and temporal scales and resolutions. In this case, as an example, we present the results for a loading or emissions model at the global scale, at a 0.5 x 0.5 latitude x longitude resolution and using input data for roughly the year 2010.

Models can simulate the situation in the past and at present, but are also powerful tools to better understand the impacts of future changes. For example, in climate policy the use of models is common practice and the results of global climate models were used as a basis for the Paris climate accords. Scenarios can be used with models to simulate and better understand future changes to a system. Exploratory scenarios enable exploration of plausible future developments (Alcamo and Jakeman, 2009), such as socioeconomic development, global environmental change (e.g. climate and land-use change) and implementation of management interventions. Normative, or also sometimes called anticipatory scenarios, enable exploration of what is

required to reach a desired end state (Alcamo and Jakeman, 2009), such as achieving the SDGs in 2030. In this case, as an example that demonstrates the opportunities of these type of analyses, we use simple, but unrealistic scenarios for the future. For most effective use in management, scenarios should be developed together with stakeholders in participative approaches (Henrichs et al., 2005; Kok et al., 2011).

The remaining part of this case study explanation describes the model and scenarios used, the results and opportunities of the application of models with scenario analysis.

The model

The Global Waterborne Pathogen model (GloWPa) estimates pathogen emissions to and concentrations in surface water. The model can be applied for different pathogens and has been applied for *Cryptosporidium* (Hofstra et al., 2013; Vermeulen et al., 2015; Hofstra and Vermeulen, 2016) and rotavirus (Kiulia et al., 2015). To simplify the case study, we focus on the human emissions of the human-specific virus rotavirus to the surface water. Rotavirus is the main contributor to the incidence of moderate to severe diarrhoea in children under five years of age (Liu et al., 2016).

Rotavirus emissions to the surface water depend on the population in a specific area, the incidence of rotavirus in the population, the sanitation system the population uses, or the lack of such a system, and the wastewater treatment that takes place. Population data are available in global databases, incidence data were summarised from the literature, data on sanitation systems used comes from the Joint Monitoring Program of WHO and UNICEF, and data on waste water treatment is available from studies on nutrient modelling that have been developed before (see Table 1).

The main equation for the emissions is as follows:

$$\text{Total Human emissions } H = P \times f_{san} \times V_p \times f_{sw} \quad (1)$$

Where P is the population of the country, f_{san} the fraction of the population using a particular type of sanitation facilities, V_p is the viral particles excretion rate per person, as explained in Section 2.1 and f_{sw} the fraction that reaches the surface water (and is not removed by waste water treatment or left behind on the land).

Four different types of emission pathways for the different sanitation facilities have been incorporated in the model. These include:

1. Connected emissions, for the population connected to a sewer. These emissions reach the surface water after treatment, or directly.
2. Direct emissions, for the population practising open defecation in urban areas or people using hanging toilets. These emissions are assumed to reach the surface water directly.
3. Diffuse emissions, for the population practicing

open defecation in rural areas. A fraction of these emissions are assumed to reach the surface water. In a further concentration model (Vermeulen et al., 2019) this fraction is adjusted based on runoff, which is dependent on precipitation, slope etcetera.

4. Onsite emissions, for the population using pit latrines and septic tanks. In this version of the model, these onsite emissions were called non-source emissions and were assumed not to reach the environment. The original rationale for this is that the waste is stored for quite some time before a pit or tank is emptied. However, in many parts of the world, a large part of the sludge from pits and tanks reaches the surface water after dumping on land or in the water (AECOM International Development Inc. and EAWAG/SANDEC, 2010). Therefore, in areas where large fractions of the population use pit latrines or septic tanks, these systems can lead to significant emissions (Okaali and Hofstra, 2018) that are not accounted for in this model. This emission pathway is currently being implemented in a future model version.

The emission pathways were developed differently for urban and rural areas, because the systems differ and because underlying data are available for urban and rural areas specifically.

For each of these emission pathways, different equations have been developed as follows:

$$\text{Connectedemissionsurban } CE_{u,age} = P_u \times f_{age} \times f_{cu} \times V_{p,age} \times 1 - f_{rem} \quad (2)$$

$$\text{Connectedemissionsrural } CE_{r,age} = P_r \times f_{age} \times f_{cr} \times V_{p,age} \times 1 - f_{rem} \quad (3)$$

$$\text{Directemissionssurban } DE_{u,age} = P_u \times f_{age} \times f_{du} \times V_{p,age} \quad (4)$$

$$\text{Directemissionssrural } DE_{r,age} = P_r \times f_{age} \times f_{dr} \times V_{p,age} \quad (5)$$

$$\text{Diffuseemissionsrural } DiFE_{r,age} = P_r \times f_{age} \times f_{difr} \times V_{p,age} \times f_{run} \quad (6)$$

Where (see Table 1 for the origin of the data):

P_u and P_r are the total urban and rural population of a country, respectively.

f_{age} is the fraction of the population for the age categories

f_{cu} and f_{cr} are the fractions of the urban and rural populations using sanitation that is connected to a sewer system (–).

f_{du} and f_{dr} are the fractions of the urban and rural populations using sanitation that is a direct source (–). As explained in Vermeulen et al. (2015), this includes WHO/UNICEF Joint Monitoring Programme (JMP) sanitation types hanging toilets (for both urban and rural population) and no facility, bush, field, unknown, elsewhere, other unimproved (for

urban population only).

- f_{diff} is the fraction of the rural population that has no sanitation facilities and forms a diffuse source (-). This includes JMP sanitation type no facility, bush, field, unknown, elsewhere, other unimproved Vermeulen et al. (2015)
- f_{run} is the fraction of feces transported with runoff from land to surface water (-). f_{run} is assumed to be 0.025, which is the median value for animal manure mobilization estimated in Ferguson et al. (2007)
- $V_{p,age}$ is the average viral particle excretion (viral particles person⁻¹ year⁻¹). V_p differs for the age categories. $V_{p,age}$ is one of the variables that could result from the other chapters in the Global Water Pathogen Project (GWPP). However, in this case it was based on a literature review on rotavirus concentrations in sewage in different parts of the world. In summary, the V_p depends on the incidence of rotavirus in the population, the length of shedding and the shedding rate of an ill person. The literature review is available in Kiulia et al. (2015). The incidence in the population is assumed to be 0.24 episodes per person per year for children younger than 5 years of age in developing countries, with a Human Development Index (HDI) lower than 0.785, 0.08 episodes per person per year for children younger than 5 years of age in industrialized countries, and 0.01 for anyone over five years of age. The episode length is assumed to be 7 days and an infected person is assumed to shed 10¹⁰ viral particles per day.
- f_{rem} is the fraction of viral particles removed by wastewater treatment (-). f_{rem} is calculated as follows:

$$f_{rem} = f_p \times RE_p + f_s \times RE_s + f_t \times RE_t \quad (7)$$

Where f_p , f_s and f_t are the fraction of primary, primary+secondary and primary+secondary+tertiary wastewater treatment systems in a country respectively, and RE_p , RE_s and RE_t are the removal efficiencies for

primary, secondary and tertiary wastewater treatment systems, respectively (-). The removal efficiencies could have come from the chapters in GWPP, but are in this study estimated from the literature as explained in Kiulia et al (2015) at 0.2, 0.975, and 0.9921, for primary, primary + secondary and primary + secondary + tertiary treatment, respectively.

The emissions were calculated separately for children younger than five years of age. In particular, the children younger than five years of age have higher incidence rates. In addition, the emissions by children wearing nappies will not reach the environment through sewage and a correction is made for that. This correction assumes that in the industrialized countries (HDI>0.785) all children wear nappies until the age of 2.5, while in developing countries only children under 2.5 years of age living in households that are connected to sewers wear nappies. The equations for the age categories are therefore as follows:

$$H = (CE_u + CE_r + DE_u + DE_r + DifE_r)/2 \text{ if HDI} > 0.785 \quad (8)$$

$$H = (CE_u/2) + (CE_r/2) + DE_u + DE_r + DifE_r, \text{ if HDI} < 0.785 \quad (8)$$

$$H_{\geq 5} = CE_{u,\geq 5} + CE_{r,\geq 5} + DE_{u,\geq 5} + DE_{r,\geq 5} + DifE_{r,\geq 5} \quad (9)$$

The total human emissions are then estimated to be:

$$H = H + H_{\geq 5} \quad (10)$$

Urban and rural human emissions are simulated for each country individually. The country emissions are then distributed over the population in the grids. The grids with the highest population density are defined to be urban grids. The distribution of sanitation facilities and treatment have assumed to be continuous across the countries.

Table 1. Data sources, reproduced from Kiulia et al. (2015)

Variable	Variable Name	Data Source
P	Population	SSP database, 2015
P_u	Urban population (Urban fraction x P)	SSP database, 2015
P_r	Rural population ((1 – urban fraction) x P)	SSP database, 2015
f_{age}	Fraction of the population younger than 5 years of age, from 5 to 14, from 15 to 25 and older than 25.	UN World Population Prospects, 2015; http://esa.un.org/wpp/Excel-Data/population.htm
HDI	Human Development Index	UNDP, 2010
f_{cu}, f_{cr}	Fraction connected (urban and rural)	WHO/UNICEF JMP data (WHO/Unicef, 2013), www.wssinfo.org) ^a
f_{du}, f_{dr}	Fraction direct (urban and rural)	WHO/UNICEF JMP data (WHO/Unicef, 2013), www.wssinfo.org) ^a
f_{diff}	Fraction diffuse (rural only)	WHO/UNICEF JMP data (WHO/Unicef, 2013), www.wssinfo.org) ^a

Variable	Variable Name	Data Source
fp	Fraction primary	(Van Drecht et al., 2009; Miller and Parker, 2013; Eurostat, 2014) as explained in Van Puijenbroek et al. (2015)
fs	primary + secondary	(Van Drecht et al., 2009; Miller and Parker, 2013; Eurostat, 2014) as explained in Van Puijenbroek et al. (2015)
ft	primary + secondary + tertiary treatment	(Van Drecht et al., 2009; Miller and Parker, 2013; Eurostat, 2014) as explained in Van Puijenbroek et al. (2015)
	Population density in a grid cell	LandScan 2010 data (Bright et al., 2011)

^aYear closest to 2010 was taken from JMP country files. When unavailable, fractions were estimated based on the fraction connected used in Van Puijenbroek et al. (2015), which were based on WHO/Unicef, (2013) supplemented with data from (Van Drecht et al., 2009; Miller and Parker, 2013; Eurostat, 2014). When incomplete (mostly missing values only around 0.01 to .02), missing values were added to non-source, or in case non-source was non-existing, to the category with the highest fraction.

Scenario analysis

Two simple scenarios have been developed for explanation of the opportunities of scenario analysis. For case studies used for decision making, new scenarios should be developed with input from planners and policy or decision makers. Such scenarios should include data on population growth, socio-economic development and sanitation interventions. An example of application of more realistic scenarios is provided in Hofstra and Vermeulen (2016).

In this case study two scenarios have been used. Scenario 1 assumes that everyone is given a sewer. However, sewage treatment is not improved, so a large part of the waste enters the surface water uncontrolled. In Scenario 2 everyone is given a sewer and tertiary treatment. Please note that these scenarios are neither realistic nor desirable. They simply serve the purpose of showing the value of scenario analysis in this case study.

Results

Total viral particle emissions to surface for approximately the year 2010 were simulated to be 2×10^{18} .

Gridded emissions reach up to 10^{17} viral particles per grid (Figure 1). Hotspot areas are the areas of the world that are most densely populated, in particular in areas of the world that have sewers without treatment or large fractions of open defecation in urban areas. These hotspots include India, Bangladesh, China, Nigeria and the coast of Latin America.

In addition to identifying hotspots, the model also enables a better understanding of main contributors of emissions. For example, looking at two countries with relatively high emissions, differences can be identified. In Nigeria a large percentage (59%) of the total 1.1×10^{17} viral particles for the year 2010 comes from open defecation in urban areas. Also open defecation in urban areas contributes 10%. It has to be taken into account that emissions from onsite systems has not been incorporated in this model, while around 55% of the population in Nigeria uses onsite systems. In the UK, country total emissions are over an order of magnitude lower, at 8.9×10^{15} viral particles for the year 2010. There the majority of the emissions are from the waste water treatment plants, that in the UK reach mostly primary+secondary treatment with an assumed 97.5% ($1.6 \log_{10}$) reduction.

Figure 2. Fraction of the emissions caused by population with access to the different sanitation types for Nigeria (top) and UK (bottom). Reproduced from Kiulia et al (2015)

The scenario plots in Figure 1 provide an overview of what would change if everyone would get a sewer (Scenario 1) or if everyone would get a sewer with tertiary treatment (Scenario 2). For Scenario 1 the total global emissions increase strongly to 9×10^{18} viral particles per year. For Scenario 2 those emissions are strongly reduced, to 8×10^{16} viral particles per year, due to the tertiary treatment everywhere.

Hotspots remain urban areas in developing countries in Scenario 1, because in those countries usually no treatment has been established and the implementation of a sewer for everyone strongly increases the emissions. In Scenario 2 also the urban areas remain the hotspots, because in these areas the populations are largest and produce the highest emissions. However, now we also see hotspots in developing countries. Tertiary treatment will remove rotavirus particles by $2.1 \log_{10}$ (99.21%), but not everything. Countries that show increases in emissions for Scenario 2, such as Finland, Japan and Uganda, have very high percentages of onsite sanitation systems right now, that have not been included in the original simulation. The assumption is that all of these people get a sewer right now, so their emissions will reach the surface water for this scenario, while they did not in the baseline.

Opportunities

Using models with scenario analysis, as presented in this case study, provides opportunities. First of all, the maps provide estimates in areas with a sparse data

availability. Secondly, the modelling enables identification of main contributors to the emissions. Basically, the link between sanitation and microbial water quality can be quantified. Thirdly, the approach allows identification of areas with high emissions, the hotspots. Understanding of such areas may help to prioritise further research and planning funding. Fourthly, the approach could support decision making. When realistic management scenarios would be developed, that also include socio-economic development and environmental changes, the global maps will show the impact of the large-scale management interventions. Additionally, the approach will help to quantify the impact of improvements on SDG indicators and understand how the SDG on safe water for all can be achieved.

This current case study provides an example for pathogen emissions to surface water. The presented model is the starting point for a concentration model to estimate the microbial water quality. Pathogen concentrations are input in health risk assessments. Together with information on exposure to the water, the health risk for the population and the resulting disease burden can be estimated (Hofstra et al., 2019). Such information is very relevant and helps to close a main research gap that quantitatively links sanitation and health through water. Better understanding the disease burden and the possible change in the disease burden due to management interventions is also relevant for stakeholders, such as planners and decision makers.

The modelling and scenario analysis approach

presented in this case study was developed for the global context, for large-scale stakeholders like WHO. The analyses at the global scale are intended to simulate spatially explicit and continuous pathogen emissions and concentrations where no data are available, to get a better understanding of areas of high concentrations (hotspots) and to understand what changes when the model input variables, such as population and sanitation, change (scenario analysis). However, the approach is flexible and can also be applied at much smaller spatial scales. Several of these analyses have been applied in data-rich areas (e.g. Whelan et al., 2014; Schijven et al., 2015). An example of an application in a data sparse area is the application to Uganda as a country (Okaali and Hofstra, 2018). Additionally, also river catchments or cities could be suitable study areas. When applying the model with scenario analysis at much smaller spatial scales it becomes relevant for more local planners and policy makers. Then the tool can identify the impact of specific management interventions on the pathogen emissions and concentrations in surface water. The tool can be used to prioritise management interventions on the ground. An app is currently in development to assist stakeholders to make better-informed decisions on safe sanitation (Rose et al.,

2019). The GWPP provides the input data on, for example, prevalence in the population and removal in waste water treatment systems, that the app translates into information useful for planners and other stakeholders.

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Hofstra, N. and Vermeulen, L. C. (2016) 'Impacts of population growth, urbanisation and sanitation changes on global human *Cryptosporidium* emissions to surface water', *International Journal of Hygiene and Environmental Health*, 219(7). doi: 10.1016/j.ijheh.2016.06.005.

The full papers can be found here: Kiulia, Hofstra et al 2015, Hofstra and Vermeulen 2016

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