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LETTER

Modelling the impact of sanitation, population growth and urbanization on human emissions of *Cryptosporidium* to surface waters—a case study for Bangladesh and India

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Abstract

Cryptosporidium is a protozoan parasite that can cause diarrhoea. Human faeces are an important source of *Cryptosporidium* in surface waters. We present a model to study the impact of sanitation, urbanization and population growth on human emissions of *Cryptosporidium* to surface waters. We build on a global model by Hofstra *et al* (2013 *Sci. Total Environ.* **442** 10–9) and zoom into Bangladesh and India as illustrative case studies. The model is most sensitive to changes in oocyst excretion and infection rate, and to assumptions on the share of faeces reaching the surface water for different sanitation types. We find urban centres to be hotspots of human *Cryptosporidium* emissions. We estimate that 53% (Bangladesh) and 91% (India) of total emissions come from urban areas. 50% of oocysts come from only 8% (Bangladesh) and 3% (India) of the country area. In the future, population growth and urbanization may further deteriorate water quality in Bangladesh and India, despite improved sanitation. Under our 'business as usual' ('sanitation improvements') scenario, oocyst emissions will increase by a factor 2.0 (1.2) for India and 2.9 (1.1) for Bangladesh between 2010 and 2050. Population growth, urbanization and sanitation development are important processes to consider for large scale water quality modelling.

1. Introduction

Cryptosporidium is a protozoan intestinal parasite that causes diarrhoea in humans and animals worldwide. In the developing world diarrhoea is the third leading cause of death (WHO 2008). But also in industrialized countries, *Cryptosporidium* outbreaks are regularly reported (Mackenzie *et al* 1994). Through faeces of infected individuals *Cryptosporidium* oocysts—the robust survival stage of the pathogen—are excreted and spread in the environment. Surface water is an important mode of environmental transport, and a source of infection when ingested as drinking water, via irrigated crops or during recreation (Medema and Schijven 2001). Ingestion of low numbers of oocysts causes a significant probability of infection (DuPont *et al* 1995). Manure from livestock, and to a lesser extent from wildlife, is a diffuse source of oocysts to surface water via runoff (Cox *et al* 2005, Thurston-Enriquez *et al* 2005). Human faeces are a point source in various ways. Sewage systems can discharge faeces in to surface water, either treated or untreated. Several treatment types (primary, secondary and tertiary) are applied with different removal rates of *Cryptosporidium* (Hofstra *et al* 2013). Faeces can also be deposited directly into the surface water, for example via hanging toilets (WHO/UNICEF JMP 2014), or they can be deposited on land when people practice open defecation, where they can be a diffuse source.

Population growth, urbanization and changes in sanitation are potentially important processes to consider for future water quality. Projections indicate that population will grow and urbanization will increase, especially in the developing world (United Nations 2014), but quantifications of the potential effects on water quality are limited. Sanitation improvements are lagging behind urbanization rates, especially in the growing number of urban slums in developing countries (WHO/UNICEF JMP 2000). The sustainable development goals aim to halve the discharge of untreated sewage and end open defecation, to limit the spread of waterborne diseases. However, data on pathogens in surface water are scarce, especially in the developing world, as monitoring is time-consuming and costly.

Global modelling of pathogen emissions to surface water could contribute to adequate sanitation management to reduce the spread of waterborne diseases. The exploratory *Cryptosporidium* emission model (Hofstra *et al* 2013) is a first global assessment of *Cryptosporidium* emissions to rivers in a spatially explicit way. This study accounts for people connected to a sewage system, but leaves out a large part of the global population, especially in developing countries, that is not connected to sewerage. This may lead to a significant underestimation of the actual situation, as a sensitivity analysis of the model showed that when assuming 20% of the faeces of the people not connected to sewer systems would end up directly into the surface water, this would almost double human *Cryptosporidium* emissions (Hofstra *et al* 2013).

Our aim is to develop a spatially explicit model to study the impact of sanitation, urbanization and population growth on human emissions of *Cryptosporidium* to surface waters. We take the model by Hofstra *et al* (2013) as starting point. We zoom into Bangladesh and India as illustrative case studies, and we apply the model in a scenario analysis to demonstrate the importance that population growth, urbanization and changes in sanitation may have for future *Cryptosporidium* emissions to surface water.

2. Methods

2.1. Description of the original Hofstra model

A full model description can be found in Hofstra *et al* (2013), here we give a short summary of the point sources sub-model, describing human emissions via sewage systems. The Hofstra model calculates the total annual emissions of *Cryptosporidium* oocysts to surface water on a 30 min grid (0.5 × 0.5 degree) for the year 2000. The model is programmed in R. Firstly, country total annual emissions are calculated, and then these are distributed over grids. The oocyst excretion rate per ill person (O_i) is set at 10^9 oocysts per person per disease episode. Infection rates (fraction of the population experiencing a disease episode per year) have been set at 10% (I_d) and 5% (I_i) for developing and industrialized countries respectively. Countries having a score of 0.785 or lower on the United Nations Development Programme's (UNDP) Human Development Index (HDI) are classified as developing countries, Bangladesh and India fall into this category. Average excretion rate (O_p) in oocysts person^{-1} yr^{-1} is then calculated as:

$$O_p = I_d \times O_i \text{ if HDI } \leqslant 0.785, \tag{1}$$

$$O_p = I_i \times O_i \text{ if HDI } > 0.785. \tag{2}$$

The fraction of oocysts removed by wastewater treatment (f_{rem}) depends on the treatment type. The Hofstra model defines four categories: no treatment (0% oocysts removed), mechanical (primary) treatment (f_p) ($R_p = 10\%$), biological (secondary) treatment (f_s) ($R_s = 50\%$) and advanced (tertiary) treatment (f_t) ($R_t = 95\%$). The fraction of sewage treatment that falls into each of the categories are country estimates based on data from WHO/UNICEF, and the fraction of oocysts removed is the weighted average of these efficiencies.

$$f_{rem} = f_p \times R_p + f_s \times R_s + f_t \times R_t. \tag{3}$$

The total human emissions per country (H) in oocysts yr^{-1} are calculated by multiplying the country population (P) connected to a sewer system (f_c) with the average oocyst excretion rate per person (O_p) in oocysts person^{-1} yr^{-1}. The fraction of oocysts removed in sewage treatment plants (STPs) is then subtracted (f_{rem}).

$$\mathrm{H} = \mathrm{P} \times f_c \times O_p \times \left(1 - f_{rem}\right). \tag{4}$$

The total human emissions per country (H) are then distributed over grid cells based on population density (taken from LandScan data maps) (Dobson *et al* 2000). This is done under the assumption that places with the highest population densities are most likely to have a sewage system. Starting at the most densely populated grid cells, the total human emissions are allocated until all have been distributed.

2.2. An improved approach to account for sanitation types

The original Hofstra model divides the population in people that are either connected or not connected to a sewage system, and the emissions of the latter are ignored. No distinction is made between populations in urban and rural areas. We propose to divide the population in four emission categories: (1) people connected to sewage systems, (2) people as a direct source of pathogens in rivers, (3) people as a diffuse source and (4) people as non-source. Furthermore, we make a distinction between urban and rural populations. To this end, we reclassify the sanitation coverage data from the Demographic and Health Survey (DHS) Program to fit our emission categories (see table 1). In classifying we assume that:

(a) Faeces of people connected to a sewage system will reach the surface water (treated or untreated). We assume different oocyst removal per treatment type, similar to the original Hofstra model.

(b) Faeces of people using septic tanks, pits or pit latrines or composting toilets will not reach the

Table 1. Four emission categories are used in our model: (1) people connected to sewage systems, (2) people as a direct source of pathogens in rivers, (3) people as a diffuse source and (4) people as non-source. This table shows how we classify the types of sanitation (following the DHS Program) for urban and rural areas into these emission categories (National Institute of Population Research and Training (NIPORT) Mitra and Associates and ICF International 2013, International Institute for Population Sciences (IIPS) and Macro International 2007).

Emission categories	Urban sanitation types based on DHS data	Rural sanitation types based on DHS data
Connected	To piped sewer system	To piped sewer system
Direct source	Hanging toilet, no facility, bush, field, unknown, elsewhere	Hanging toilet
Diffuse source	–	No facility, bush, field, unknown, elsewhere
Non-source	To septic tank, to pit, pit latrine, composting toilet	To septic tank, to pit, pit latrine, composting toilet

surface water. Soil passage effectively retains protozoan (oo)cysts (Ferguson *et al* 2003). Furthermore, long storage time in septic tanks and latrines can cause oocyst die-off, and routes of disposal of contents are largely unknown. Therefore, we assume emissions to surface water of people using these systems to be zero.

(c) Faeces of people using hanging toilets are a direct source of oocysts to the surface water. These are systems where a toilet facility is built above a stream or lake and faeces drop directly into the water.

(d) Faeces of people without sanitation facilities are a direct source of oocysts in urban areas and a diffuse source in rural areas. In urban areas faeces of people without sanitation facilities likely end up in the surface water (e.g. via open drains), due to the lack of space for open defecation on land. In rural areas, these emissions are likely to end up on the land and can form a diffuse source similar to animal manure (Thurston-Enriquez *et al* 2005). Therefore, we classify the sanitation categories 'unknown', 'elsewhere' or 'no facilities, bush, field' to the diffuse sources for rural populations and to the direct sources for urban populations.

2.3. Estimating *Cryptosporidium* emissions in 2010

Using the assumptions above, we calculate human *Cryptosporidium* emissions to the surface water in Bangladesh and India for the year 2010. These countries were chosen as illustrative examples of developing countries with high population density and urbanization rates where a variety of different sanitation types are used, and because Hofstra *et al* (2013) indicated this region as one with emission hot-spots.

We use the formula by Hofstra *et al* (2013) for the calculation of the human emissions via sewage systems, but calculate this for urban and rural areas separately. In addition, we calculate direct and diffuse emissions. This results in the following equations:

$$\text{Connected emissions urban } CE_\mathrm{u} = P_\mathrm{u} \times f_\mathrm{cu} \times O_\mathrm{p} \times \left(1 - f_\mathrm{rem}\right), \tag{5}$$

$$\text{Connected emissions rural } CE_\mathrm{r} = P_\mathrm{r} \times f_\mathrm{cr} \times O_\mathrm{p} \times \left(1 - f_\mathrm{rem}\right), \tag{6}$$

$$\text{Direct emissions urban } DE_\mathrm{u} = P_\mathrm{u} \times f_\mathrm{du} \times O_\mathrm{p}, \tag{7}$$

$$\text{Direct emissions rural } DE_\mathrm{r} = P_\mathrm{r} \times f_\mathrm{dr} \times O_\mathrm{p}, \tag{8}$$

$$\text{Diffuse emissions rural } DifE_\mathrm{r} = P_\mathrm{r} \times f_\mathrm{difr} \times O_\mathrm{p} \times f_\mathrm{run}, \tag{9}$$

$$\text{Total human emissions } H = CE_\mathrm{u} + CE_\mathrm{r} + DE_\mathrm{u} + DE_\mathrm{r} + DifE_\mathrm{r}, \tag{10}$$

where: O_p is the average oocyst excretion (oocysts person^{-1} yr^{-1}). It is calculated as described above (equations (1) and (2)), f_rem is the fraction of oocysts removed by sewage treatment. It is calculated as described above (equation (3)), P_u and P_r are the total urban and rural population of a country, respectively (equations (5)–(9)), f_cu and f_cr are the fractions of the urban and rural populations that make use of sanitation that is connected to a sewer system. (equations (5) and (6)), f_du and f_dr are the fractions of the urban and rural populations that make use of sanitation that is a direct source (equations (7) and (8)), f_difr is the fraction of the rural population that has no sanitation facilities and forms a diffuse source (equation (9)) and f_run is the fraction of faeces transported with runoff from land to surface water (equation (9)).

We have updated the baseline of the model to the year 2010. In tables A1 and A2 in the appendix all parameter values used in the calculations can be found. Oocyst excretion per ill person and oocyst removal efficiencies by different sewage treatment levels equal the original values as estimated by Hofstra *et al* (2013). We assume that of the population connected to sewage systems, 20% receives treatment and the rest reaches the surface water untreated. This estimate is in line with the estimates for sewage treatment in Indian cities (Central Pollution Control Board: Government of India 2015), although treatment levels are not specified here. Dhaka, the capital of Bangladesh, reportedly has only one STP with a capacity to treat only a third of the collected wastewater, and sewage overflows occur regularly (WASH-plus project of USAID 2010). Data on sewage treatment in other regions of Bangladesh is difficult to find, therefore we take the same value of 20% to represent Bangladesh also. We assume that currently only primary sewage treatment exists in India and Bangladesh.

We set the infection rate to 5%, lower than the 10% assumed by Hofstra *et al* (2013) for developing countries. We based this on a short literature review on cryptosporidiosis prevalence, finding that 2.1–3.5% of diarrhoea cases in Bangladesh and India are caused by *Cryptosporidium* (Rahman *et al* 1990, Bhattacharya *et al* 1997, Haque *et al* 2009, Ajjampur et al 2010a). Ajjampur et al (2010b) found that 40% of children experience multiple episodes of cryptosporidiosis, and more generally, children in developing countries are estimated to have on average 2.9 episodes of diarrhoea per year (Fischer Walker et al 2012), meaning that an overall annual *Cryptosporidium* infection rate of 10% may be correct for children. However, for adults it is likely lower, Fischer Walker and Black (2010) reported a median incidence of 0.299–0.675 episodes of diarrhoea per year for adults and children >5 years in the South and South East Asia region. This means that a 10% overall annual infection rate is probably too high for Bangladesh and India. Therefore we decided to set the overall annual infection rate to 5%.

We run the model using sanitation input data per state instead of national averages, dividing Bangladesh in 7 and India in 35 regions (see table A2 for an overview). The data on urban and rural populations per state are from the Bangladesh Bureau of Statistics and the Census of India (Bangladesh Bureau of Statistics 2011, Census of India 2011). For data on the usage of different sanitation types we take the most recent estimates of the DHS Program, this is for Bangladesh the year 2011 and for India 2005–2006 (International Institute for Population Sciences (IIPS) and Macro International 2007, National Institute of Population Research and Training (NIPORT), Mitra and Associates and ICF International 2013). The runoff fraction is based on the median value for mobilization of *Cryptosporidium* from animal manure by Ferguson et al (2007). We study the effect of uncertainty in model input parameters in a sensitivity analysis (section 3.3).

2.4. Spatial distribution of emissions in 2010

We estimate the spatial distribution of oocyst emissions to the surface water in Bangladesh and India. We spatially identify a country's urban and rural populations via density ranking, where the population in the most densely populated grid cells is defined as urban, based on a LandScan density map (Bright et al 2011). We assume that among a population defined as urban, sanitation is distributed equally, proportional to the occurrence of different sanitation types.

2.5. Estimating *Cryptosporidium* emissions in 2050

We calculate the potential effect of urbanization, population growth and sanitation changes on future human *Cryptosporidium* emissions for Bangladesh and India. We define two scenarios:

1. Business as usual: we assume that in 2050 the percentage of people connected to the different sanitation types in urban and rural areas is the same as today. Sewage treatment levels have also stayed the same (only primary treatment).
2. Sanitation improvements: in 2050 open defecation is no longer practiced, and hanging toilets are no longer used. In urban areas, the population that previously used either of these sanitation types are now mostly connected to the sewage system (75%) or use on-site systems such as septic tanks and latrines (25%). In rural areas it is the other way around, it is more likely people use on-site systems (75%) than sewer connections (25%). Sewage treatment levels have improved, one third is primary treatment, one third secondary and one third tertiary treatment. Improvement of sanitation is in line with the current trends observed in the DHS data.

For both scenarios we use the population and urbanization estimates for 2050 based on the Global Orchestration (GO) scenario of the Millennium Ecosystem Assessment. This scenario assumes globalization and reactive environmental management, as opposed to regionalization and proactive environmental management (Alcamo et al 2006).

3. Results

3.1. Accounting for sanitation types

We divide the urban and rural populations of Bangladesh and India in different model emission categories (connected, direct source, diffuse source, non-source) based on sanitation types according to the DHS Program. Figure 1 shows that only accounting for people connected to a sewage system, as was done in the original Hofstra model, may lead to a large underestimation of human emissions in India and Bangladesh. The figure also shows large differences exist between sanitation types in urban and rural populations and between countries.

3.2. *Cryptosporidium* emissions in 2010

Total annual human *Cryptosporidium* emissions to the surface water in 2010 are for Bangladesh 1.0×10^{15} and for India 1.2×10^{16}, according to our model. In Bangladesh, of these total emissions 18% comes from the population connected to a sewage system, 81% from direct sources and 1% from diffuse sources. 53% of the total emissions of Bangladesh is urban. In India, of these total emissions 61% comes from the population connected to a sewage system, 32% from direct sources and 7% from diffuse sources. 91% of the total Indian emissions is urban. Compared to the original Hofstra et al (2013) estimate for 2000, our 2010 estimate for India is 1.5 times higher and for Bangladesh 8.6 times higher.

3.3. Sensitivity analysis

We studied the sensitivity of model output to changes in ten input parameters. Each parameter can take three different values in the sensitivity analysis, based on reasonable ranges the parameter can take (table A1). We do the analysis in pairs of parameters, changing one or both at a time, as some parameters are strongly

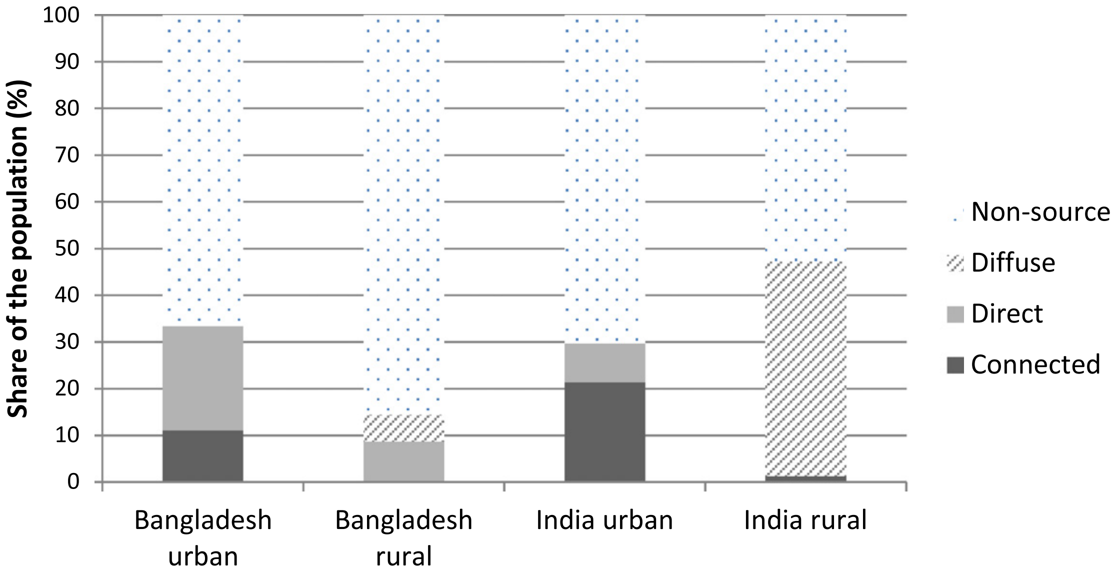

Figure 1. Share (%) of the population of Bangladesh and India in model emission categories, based on sanitation types. Data on sanitation types by the DHS Program were classified to fit the model emission categories (1) connected to a sewage system, (2) direct emission to the surface water (hanging toilets and for urban people the DHS categories 'unknown', 'elsewhere' or 'no facilities, bush, field'), (3) diffuse sources (for rural people the DHS categories 'unknown', 'elsewhere' or 'no facilities, bush, field') and (4) non-source (the DHS categories 'to septic tank', 'composting toilet', 'to pit' and 'to pit latrine').

related to others. For example, the effect on model output of changing coverage of different sewage treatment levels (primary, secondary, tertiary) depends on the removal efficiencies assumed for these levels. Results of the sensitivity analysis are presented in table A3. For both Bangladesh and India, the model was most sensitive to changes in the combination of oocyst excretion and number of infections. As these numbers are highly variable and uncertain (shown for 1 log unit change in oocyst excretion and halving or doubling of infection rate), the effect on model outcome is large, up to 20-fold increases or decreases. Uncertainty in whether faeces from septic tanks and pit latrines can reach the surface water can triple total oocyst emissions for Bangladesh. Uncertainty in the share of the faeces of people without sanitation facilities that reaches surface waters was a large contributor to uncertainty for India, mainly due to the large rural population without facilities.

3.4. Spatial distribution of emissions in 2010

Urban areas in both Bangladesh and India are hotspots of *Cryptosporidium* emissions to surface water. This is visualized in figure 2, showing the spatial distribution of oocyst emissions over a 0.5 × 0.5 degree grid. Local differences in calculated oocyst emissions are large; in India 50% of oocysts originate from only 3% of grid cells, and 90% of oocysts originate from 12% of the grid cells. In Bangladesh the result is less extreme: 50% of oocysts originate from 8% of the grid cells and 90% of oocysts originate from 59% of the grid cells. This is because Bangladesh has a more evenly distributed population than India in the LandScan population density map.

3.5. Scenario analysis of future oocyst emissions

In the 'Business as usual' scenario the calculated total human emissions of oocysts to surface water for Bangladesh and India are higher in 2050 than in 2010 (figure 3). According to our model oocyst emissions will increase by a factor 2.0 (India) and 2.9 (Bangladesh) in this period. This is mainly attributable to an expected increase in urban emissions of oocysts by a factor 2.1 (India) and 4.5 (Bangladesh). The calculated increase is solely due to population growth and urbanization, as sanitation coverage is assumed to increase proportionally with population and urbanization.

In the 'sanitation improvements' scenario the calculated total human emissions for 2050 compared to 2010 are slightly higher for both Bangladesh (factor 1.1) and India (factor 1.2). For India, urban emissions go down slightly (factor 0.9) but rural emissions increase by a factor 4.0, because India had a very large population practicing open defecation that are now assumed to be partly connected to a sewage system.

4. Discussion

To our knowledge, our model currently gives the only available estimate for *Cryptosporidium* oocyst emissions to surface water in Bangladesh and India. Our model can be used for pinpointing hotspot areas where problems may be largest, comparing pollution from different regions, and indicating dominant pollution sources now and in the future. The model can be informative for sanitation and water quality managers. The model in its current form is less appropriate for getting accurate emission values for specific locations within these countries, as uncertainties in this type of

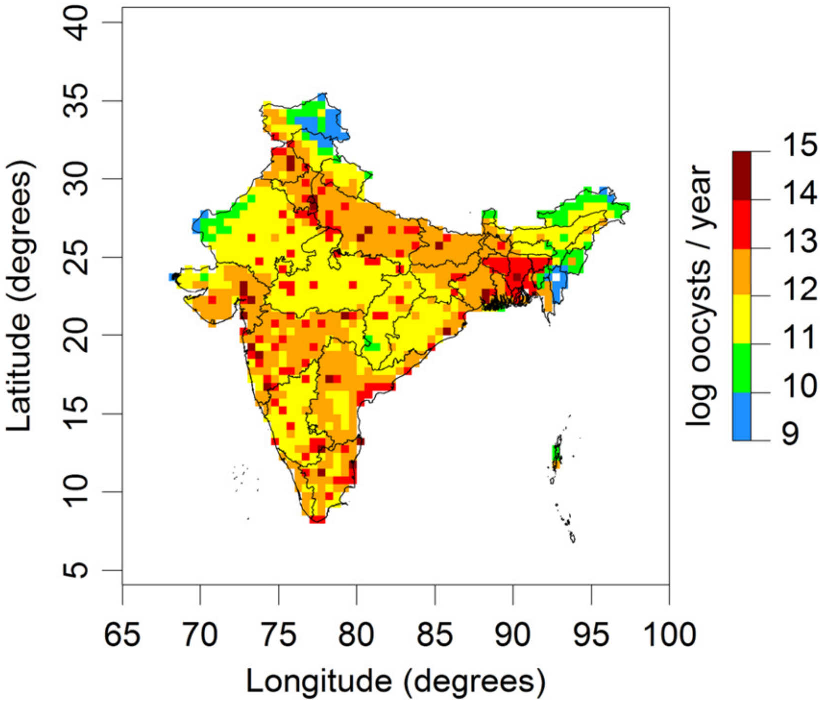

Figure 2. Spatial distribution of human oocyst emissions to the surface water in India and Bangladesh. This map shows log total annual human oocyst emissions to the surface water on a 0.5 × 0.5 degree grid, representing conditions for the year 2010. Emissions are distributed proportional to population size from a LandScan population density map (Bright *et al* 2011). The results are calculated using population, urbanization and sanitation data per state, dividing Bangladesh in 7 and India in 35 regions (borders shown on map).

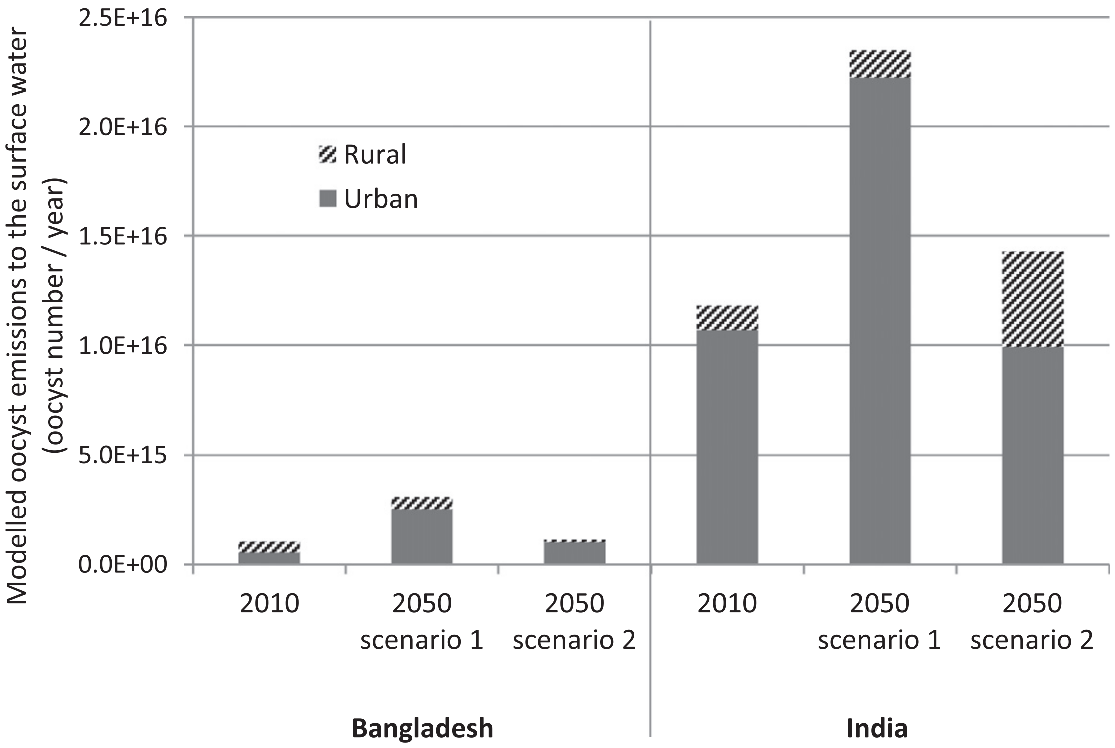

Figure 3. Total annual human *Cryptosporidium* oocyst emissions to surface water from urban and rural sources in Bangladesh and India in 2010 and for two scenarios in 2050, (1) 'business as usual' and (2) 'sanitation improvements'.

modelling research are inevitably large. This is due to quality and availability of input data and model assumptions, among others. Oocyst excretion rates are highly uncertain. We assume a single annual oocyst excretion rate, as is done by Hofstra *et al* (2013). This approach does not account for potential regional outbreaks of *Cryptosporidium* nor for variation in endemic cryptosporidiosis and shedding of oocysts.

However, we did adjust the general infection rate estimate used in Hofstra *et al* (2013) to be more representative for the situation in Bangladesh and India. Our categorization of sanitation types assumes oocysts that end up in the soil through pit latrines and the like will not reach the surface water, but interflow may transport the faeces there (Davies *et al* 2004), and in case of heavy rainfall these systems may flood. We ignore the contribution from septic tanks, it is assumed they are emptied in such a way the contents do not reach the surface water (e.g. in landfills) or after a long enough time for the oocysts to be inactivated. In addition, we classify the sanitation categories ‘unknown’, ‘elsewhere’ or ‘no facilities, bush, field’ to the diffuse sources for rural populations and to the direct sources for urban populations, based on the premise that due to lack of space in crowded urban areas it is likely that faeces will be disposed of towards the surface water. It is difficult to verify such assumptions, as regional or cultural variation in the use of sanitation can be large and the topic is often taboo (Dellström Rosenquist 2005). In India 597 million people practice open defecation (WHO/UNICEF JMP 2014). The uncertainty about what happens with these faeces is large, and can significantly influence model outcomes, as was shown in our sensitivity analysis. The fraction of faeces on land that is transported to surface water via runoff is dependent on geographical and climatic factors, such as slope and precipitation, which we have not taken into account in this study. Furthermore, measurement data to validate model outcomes are not available, to our knowledge. To improve our model, we would particularly require more data on oocyst excretion and the occurrence of cryptosporidiosis, data on the effect of different sanitation systems on pathogen survival, and measurements of pathogens in sewage and surface water for model validation.

Urban areas are hotspots of *Cryptosporidium* emissions; we estimate that in Bangladesh 53% and in India 91% of total emissions come from urban areas. The original Hofstra model spatially distributed point source sewer emissions over the most densely populated areas in a country only. By calculating at the state level, including a division between urban and rural populations, including direct and diffuse sources, and distributing proportionally to population size, we now produce a map that represents spatial distribution of oocyst emissions more accurately, as a larger share of the population is accounted for and the location of more population centres is represented.

The most problematic areas with regards to safe disposal of human faeces are likely to be urban slums. An urban slum can be defined as ‘an informal settlement in a city or town characterized by poor urban infrastructure, low water and sanitation service levels, high population density and limited access for basic services’ (Katukiza *et al* 2013). It is questionable whether the DHS data on urban sanitation in Bangladesh and India also hold for slum areas, as actual surveys done in slums are scarce. According to UN Habitat, in India 29.4% and in Bangladesh 61.6% of urban population lived in a slum in 2009 (Global Health Observatory Data Repository 2009). A Bangladesh slum population survey identified 9048 slum communities in the six major cities (Angeles *et al* 2009). Hanchett *et al* (2003) found that only 6–12% of households in slums of two Bangladesh cities has access to any form of latrines, septic tanks or sewerage, while the WHO/UNICEF JMP reports 50% overall urban access to improved sanitation in the year 2000 for Bangladesh (WHO/UNICEF JMP 2014). Similarly, Agarwal (2011) found that for urban areas in India, less than half of the poorest urban quartile had a flush toilet or pit latrine, while over 95% of the rest of the urban population did have this facility in 2005–2006. Furthermore, individual cities can differ in provision levels of basic services like sanitation, with smaller cities being generally underserved (Panel on Urban Population Dynamics 2003). These examples highlight the inequalities between the richer and poorer urban populations, and the consequent difficulties for accurate spatial assessment of pollution originating from these areas. By categorizing the emissions of the urban population without sanitation access to the direct sources, we try to capture these slum populations in our model. It seems likely that part of the faeces from slums end up directly in surface waters (Nath 2003, Nyenje *et al* 2010), since sanitation coverage is low and there is little space for it to end up in the soil. In future, the problem will increase; it is expected that the number of people living in slums worldwide will have doubled by 2030 compared to 2000 (UN Millennium Project 2005). The rate of urbanization is so rapid that in developing countries planned urban expansion cannot keep up (UNEP/UN-HABITAT 2010).

Sanitation coverage is improving in most world regions (WHO/UNICEF JMP 2014). However, if more people are connected to sewers, this does not mean that adequate sewage treatment will also be installed (WHO/UNICEF JMP 2000, Baum *et al* 2013). A sewer connection without sewage treatment can cause faeces that now end up in the soil to reach the surface water untreated and affect water quality. More droughts and extreme rainfall events, which are expected with climate change, can cause problems for the existing STPs in the developing world, which are often old (UNEP/UN-HABITAT 2010). Both in developing and developed countries rainfall events can cause sewer overflows, causing wastewater that was supposed to go to a STP to reach the surface water untreated. When flooding occurs, waste from open and inadequate sewers or other sanitation types will run off to lower-lying areas (UNEP/UN-HABITAT 2010). This process is enhanced by urbanization, because there will be more impervious surfaces inhibiting the water to infiltrate into the soil (Nyenje *et al* 2010). Our current model does not incorporate rainfall event occurrence, as we are studying annual total emissions. Other models studying waterborne pathogens at catchment scale at smaller time steps do incorporate this (e.g. Petersen *et al* 2009).

The sensitivity analysis done by Hofstra *et al* showed that the fate of faeces of people not connected to a sewage system may impact model outcomes considerably. In this study, we quantified this contribution for Bangladesh and India: we estimate that emissions from people not connected to a sewage system constitute 82% (Bangladesh) and 39% (India) of total emissions. Our scenario analysis highlights the importance of taking into account population growth, urbanization and sanitation changes when predicting future water quality. We show that even with sanitation improvements (ending open defecation, improving sewage treatment levels) *Cryptosporidium* emissions to surface water are likely to increase.

5. Conclusion

In this paper we propose a new method to calculate human emissions of *Cryptosporidium* to surface water, using a modified version of the Hofstra point sources sub-model. We modify the model by calculating human *Cryptosporidium* emissions using categorized DHS data on sanitation use per state, updating the baseline to 2010, adding direct and diffuse emissions, introducing a division between urban and rural populations, and creating a new spatial distribution.

Taking Bangladesh and India as case studies, we show that only accounting for people connected to a sewage system, as was done in the original Hofstra model, may lead to a large underestimation of human emissions in developing countries. Sewer connections with inadequate treatment, but also hanging toilets and open defecation negatively affect water quality. Urban centres are hotspots of human *Cryptosporidium* emissions in Bangladesh and India; we estimate that 53% (Bangladesh) and 91% (India) of total emissions come from urban areas. Our map indicates that 50% of oocysts originate from only 8% (Bangladesh) and 3% (India) of the country area. Future population growth and urbanization are likely to lead to further deterioration of water quality in Bangladesh and India, in spite of efforts to improve sanitation. Under our 'Business as usual' scenario, oocyst emissions will increase by a factor 2.0 for India and 2.9 for Bangladesh between 2010 and 2050. Under our 'sanitation improvements' scenario, oocysts emissions increase slightly for both Bangladesh (factor 1.1) and India (factor 1.2). The model is most sensitive to changes in oocyst excretion and infection rate, as well as assumptions on what share of faeces reaches the surface water for different sanitation types.

Population growth, urbanization and the development of sanitation are important processes to consider for large scale modelling of current and future water quality related to human faeces. The new method proposed here is a first step for improved spatially explicit modelling of *Cryptosporidium*.

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Appendix

Table A1. Model parameter values for the standard model run and the sensitivity analysis for 2010. The sensitivity analysis is done with pairs of parameters that can take three different values each (see table A2 for results). 'Standard value' indicates that the same value as in the standard model run is taken. Estimates for oocyst excretion and the removal efficiencies of oocysts by sewage treatment are based on a literature study by Hofstra *et al* (2013). The infection rate and the percentage of the connected population that receives treatment were estimated from literature (section 2.3).

		Sensitivity		
	Model parameter value	Value 1	Value 2	Value 3
Oocyst excretion (oocysts / infected person)	1.00E+09	Low (−1log) 1.00E+08	Standard value	High (+1log) 1.00E+10
Infection rate (% of population infected)	5	Low (half) 2.5	Standard value	High (double) 10
Oocyst removal efficiencies sewage treatment (%)		Low	Standard value	High
Primary treatment	10	4		90
Secondary treatment	50	28		100
Tertiary treatment	95	40		99
Percentage of connected population with primary treatment (%)	20	Standard value	0	0
Percentage of connected population with secondary treatment (%)	0	Standard value	20	Standard value
Percentage of connected population with tertiary treatment (%)	0	Standard value	Standard value	20
Urban no facilities that reaches surface water (%)	100	Standard value	75	50
Rural no facilities that reaches surface water (%)	2.5	0	25	50
Urban septic tank and pit latrine content that reaches surface water (%)	0	Standard value	25	50
Rural septic tank and pit latrine content that reaches surface water (%)	0	Standard value	25	50

Table A2. Model parameter values per state. The data on urban and rural populations per state are from the Bangladesh Bureau of Statistics and the Census of India (Bangladesh Bureau of Statistics 2011, Census of India 2011). The sanitation numbers in this table are fractions of the population that use sanitation that fall into the emission categories 'connected', 'direct', 'diffuse' and 'non-source', as described in section 2.2. Data on the usage of different sanitation types are based on the most recent estimates of the DHS Program, this is for Bangladesh the year 2011 and for India 2005–2006 (National Institute of Population Research and Training (NIPORT) Mitra and Associates and ICF International 2013, International Institute for Population Sciences (IIPS) and Macro International 2007). Indian regions for which no sanitation data were available have for modelling purposes been assigned the population-weighted average Indian sanitation.

					Sanitation						
		Population			Urban			Rural			
Region	Administrative level	Total	Urban	Rural	Connected	Direct	Non-source	Connected	Direct	Diffuse	Non-source
India total	Country	1.21E+09	3.77E+08	8.33E+08	0.21	0.08	0.70	0.01	0.00	0.46	0.53
Andaman and Nicobar Islands	Union territory	379 944	135 533	244 411	NA	NA	NA	NA	NA	NA	NA
Andhra Pradesh	State	84 665 533	28 353 745	56 311 788	0.48	0.15	0.37	0.02	0.00	0.73	0.25
Arunachal Pradesh	State	1 382 611	313 446	1 069 165	0.09	0.12	0.80	0.03	0.00	0.32	0.65
Assam	State	31 169 272	4 388 756	26 780 516	0.02	0.03	0.95	0.00	0.00	0.29	0.71
Bihar	State	1.04E+08	11 729 609	92 075 028	0.08	0.28	0.64	0.01	0.00	0.84	0.16
Chandigarh	Union territory	1 054 686	1 025 682	29 004	NA	NA	NA	NA	NA	NA	NA
Chhattisgarh	State	25 540 196	5 936 538	19 603 658	0.03	0.36	0.61	0.00	0.00	0.94	0.06
Dadra and Nagar Haveli	Union territory	342 853	159 829	183 024	NA	NA	NA	NA	NA	NA	NA
Daman and Diu	Union territory	242 911	182 580	60 331	NA	NA	NA	NA	NA	NA	NA
Delhi	Union territory	16 753 235	16 333 916	419 319	0.67	0.23	0.10	0.17	0.00	0.35	0.49
Goa	State	1 457 723	906 309	551 414	0.02	0.17	0.81	0.02	0.00	0.40	0.57
Gujarat	State	60 383 628	25 712 811	34 670 817	0.61	0.14	0.25	0.05	0.00	0.70	0.25
Haryana	State	25 353 081	8 821 588	16 531 493	0.52	0.12	0.36	0.01	0.00	0.65	0.34
Himachal Pradesh	State	6 856 509	688 704	6 167 805	0.26	0.11	0.63	0.01	0.00	0.60	0.39
Jammu and Kashmir	State	12 548 926	3 414 106	9 134 820	0.14	0.26	0.59	0.02	0.00	0.51	0.47
Jharkhand	State	32 966 238	7 929 292	25 036 946	0.06	0.29	0.64	0.00	0.00	0.95	0.05
Karnataka	State	61 130 704	23 578 175	37 552 529	0.23	0.20	0.57	0.00	0.00	0.79	0.21
Kerala	State	33 387 677	15 932 171	17 455 506	0.01	0.02	0.97	0.02	0.00	0.05	0.93
Lakshadweep	Union territory	64 429	50 308	14 121	NA	NA	NA	NA	NA	NA	NA
Madhya Pradesh	State	72 597 565	20 059 666	52 537 899	0.37	0.20	0.43	0.00	0.00	0.90	0.09
Maharashtra	State	1.12E+08	50 827 531	61 545 441	0.72	0.12	0.17	0.02	0.00	0.80	0.19
Manipur	State	2 721 756	822 132	1 899 624	0.01	0.02	0.98	0.00	0.00	0.09	0.91
Meghalaya	State	2 964 007	595 036	2 368 971	0.01	0.03	0.96	0.00	0.00	0.40	0.59
Mizoram	State	1 091 014	561 977	529 017	0.00	0.00	1.00	0.00	0.00	0.05	0.95
Nagaland	State	1 980 602	573 741	1 406 861	0.01	0.06	0.93	0.01	0.00	0.23	0.76
Odisha	State	41 947 358	6 996 124	34 951 234	0.09	0.42	0.49	0.00	0.00	0.89	0.11
Puducherry	Union territory	1 244 464	850 123	394 341	NA	NA	NA	NA	NA	NA	NA

Table A2. (Continued.)

					Sanitation						
		Population			Urban			Rural			
Region	Administrative level	Total	Urban	Rural	Connected	Direct	Non-source	Connected	Direct	Diffuse	Non-source
Punjab	State	27 704 236	10 387 436	17 316 800	0.71	0.08	0.22	0.01	0.00	0.44	0.54
Rajasthan	State	68 621 012	17 080 776	51 540 236	0.18	0.20	0.63	0.00	0.00	0.92	0.08
Sikkim	State	607 688	151 726	455 962	0.35	0.01	0.64	0.02	0.00	0.16	0.83
Tamil Nadu	State	72 138 958	34 949 729	37 189 229	0.26	0.50	0.24	0.00	0.00	0.83	0.16
Tripura	State	3 671 032	960 981	2 710 051	0.00	0.02	0.97	0.00	0.00	0.04	0.96
Uttar Pradesh	State	2E+08	44 470 455	1.55E+08	0.21	0.26	0.53	0.00	0.00	0.84	0.16
Uttarakhand	State	10 116 752	3 091 169	7 025 583	0.43	0.08	0.49	0.02	0.00	0.58	0.41
West Bengal	State	91 347 736	29 134 060	62 213 676	0.33	0.05	0.62	0.00	0.00	0.55	0.45
Bangladesh total	Country	1.44E+08	33 563 183	1.1E+08	0.11	0.22	0.67	0.00	0.09	0.06	0.86
Barisal	Division	8 325 666	1 361 943	6 963 723	0.02	0.05	0.94	0.00	0.09	0.02	0.89
Chittagong	Division	28 423 019	6 905 480	21 517 539	0.02	0.26	0.72	0.00	0.06	0.03	0.91
Dhaka	Division	47 424 418	15 584 835	31 839 583	0.21	0.32	0.47	0.00	0.12	0.06	0.81
Khulna	Division	15 687 759	2 822 121	12 865 638	0.03	0.03	0.95	0.00	0.04	0.03	0.93
Rajshahi	Division	18 484 858	3 317 022	15 167 836	0.01	0.08	0.91	0.00	0.09	0.05	0.86
Rangpur	Division	15 787 758	2 109 071	13 678 687	0.00	0.11	0.88	0.00	0.04	0.14	0.81
Sylhet	Division	9 910 219	1 462 711	8 447 508	0.07	0.06	0.87	0.00	0.14	0.05	0.81

Table A3. Sensitivity analysis results. We test the sensitivity of our modelled *Cryptosporidium* human emissions for Bangladesh and India to changes in a number of model parameters. The numbers shown are percentage change in oocyst emissions compared to the standard run (0). Positive numbers are therefore increases, negative numbers are decreases. We do the sensitivity analysis in pairs of parameters, changing one or both at a time, as some parameters are strongly related to one another. Parameters can take three different values each (table A1). The first series shows changes in sewage treatment (all currently connected people switch to secondary or tertiary treatment) and removal efficiencies of *Cryptosporidium* during treatment (based on the ranges found by Hofstra *et al* 2013: primary 4–90%, secondary 28–100%, tertiary 40–99%). The second series shows changes in whether or not the 'no facilities' category emissions reach the surface water. The third series shows changes in whether or not the 'septic tanks and pit latrines' category emissions reach the surface water. The fourth series shows changes in country population and urban population sizes (10% lower or higher). The fifth series shows changes in *Cryptosporidium* oocyst excretion (1 log unit lower or higher) and the number of infections (half or double). Each series contains nine individual model runs, leading to a total of 45 runs per country.

		Bangladesh			India		
		Removal efficiencies					
		Low	*Middle*	*High*	*Low*	*Middle*	*High*
Sewage treatment	*Current situation (primary only)*	0	0	-3	1	0	-10
	All switch to secondary	-1	-1	-3	-2	-5	-11
	All switch to tertiary	-1	-3	-3	-4	-11	-11
		Share of faeces from rural population without facilities that reaches surface waters					
		0%	*25%*	*50%*	*0%*	*25%*	*50%*
Share of faeces from urban population without facilities that reaches surface waters	*100%*	-1	7	14	-8	68	143
	75%	-10	-2	5	-16	60	136
	50%	-19	-11	-4	-23	52	128
		Share of rural septic tank and pit latrine content that reaches surface waters					
		0%	*25%*	*50%*	*0%*	*25%*	*50%*
Share of urban septic tank and pit latrine content that reaches surface waters	*0%*	0	115	229	0	26	51
	25%	27	142	256	17	42	68
	50%	54	169	284	33	59	85
		Urbanisation					
		Low (-10%)	*Middle*	*High (+10%)*	*Low (-10%)*	*Middle*	*High (+10%)*
Population size	*Low (-10%)*	-22	-10	2	-34	-10	14
	Middle	-13	0	13	-27	0	27
	High (+10%)	-4	10	24	-20	10	40
		Number of infections					
		Low (half)	*Middle*	*High (double)*	*Low (half)*	*Middle*	*High (double)*
Oocyst excretion per infected individual	*Low (-1log)*	-95	-90	-80	-95	-90	-80
	Middle	-50	0	100	-50	0	100
	High (+1log)	400	900	1900	400	900	1900

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