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Present and Future Human Emissions of Rotavirus and *Escherichia coli* to Uganda's Surface Waters

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Abbreviations: BS, baseline conditions; CFU, colony-forming units; CWTP, conventional wastewater treatment plant; DEC, diarrheagenic *Escherichia coli*; EC, *Escherichia coli*; NWSC, National Water and Sewerage Corporation; RV, rotavirus; SFD, shit flow diagram; WSP, wastewater stabilization pond.

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Core Ideas

Rotavirus and *E. coli* emissions from sanitation facilities reach surface water.

Using modeling and scenario analysis, we simulated these emissions for Uganda.

High-emission areas are Kampala and other urban areas.

A new model including onsite sanitation shows higher emissions in Kampala.

Future emissions are reducible through sanitation planning.

ABSTRACT

Rotavirus (RV) and diarrheagenic *Escherichia coli* are waterborne pathogens commonly causing diarrhea in children below five years old worldwide. Our study is a first step toward a loads–concentrations–risk modeling and scenario analysis framework. We analyzed current and future human RV and indicator *E. coli* (EC) emissions from sanitation facilities to surface waters in Uganda using two process-based models. Emissions were estimated for the baseline year 2015 and for three scenarios in 2030 using population, excretion rates, sanitation types, and wastewater treatment. The first model is a downscaled GloWPa-Rota H1 version, producing emissions at a 1-km^2 resolution. The second model is newly developed for Kampala and adds emissions from pit latrines and septic tanks excluded in the first model. The scenarios Business as Usual, Industrious, and Low Emissions reflect government prospects in sanitation coverage and wastewater treatment. For the first model, 6.14×10^{14} RV particles d^{-1} and 1.31×10^{12} EC colony-forming units (CFU) d^{-1} are emitted to surface waters in 2015. The RV emissions are expected to increase in 2030 by 75% for Business as Usual and 212% for Industrious and decrease by 58% in Low Emissions. Emissions from the second model are higher for Kampala than in the first model, at 3.74×10^{14} vs. 5.95×10^{13} RV particles d^{-1} and 8.18×10^{11} vs. 1.75×10^{11} EC CFU d^{-1} in 2015, most of which come from the onsite-not-contained category. Simulated emissions for Kampala show the importance of including onsite sanitation in our modeling. Our study is replicable in other locations and helps identify key emission sources, their hotspots, and the importance of wastewater treatment. The scenarios can guide future sanitation safety planning.

Rotavirus (RV) and diarrheagenic *Escherichia coli* (DEC) are among the common causes of pediatric diarrhea worldwide (Nataro and Kaper, 1998; Rodrigues et al., 2002). These waterborne pathogens kill about 1.5 million children annually due to gastroenteritis and dysentery (Hodges and Gill, 2010). Group A RV particularly causes acute gastroenteritis in children under five years old (Rodrigues et al., 2002), and any infected person excretes 10^{10} to 10^{12} RV particles per gram of feces (Bishop, 1996). Nataro and Kaper (1998) showed that DEC is differentiated from commensal *E. coli* (EC) by serotyping, biochemical reactions, virulence screening, diarrhea symptoms, and patient age. Escherichia coli is a thermotolerant coliform known to indicate fecal contamination from warm-blooded animals. Humans maintain a density of 10^6 to 10^9 EC colony-forming units (CFU) per gram of feces (Savageau, 1983). We focused on EC in our study rather than DEC, due to limited data on DEC excretion and incidence rates. Contaminated water, food, and person-to-person contact are known pathways for RV and EC transmission, via the fecal–oral route (Cáceres et al., 1998). Human emissions of RV and EC reach surface water through open defecation, poor fecal sludge disposal, and partially treated wastewater effluent (Williams and Overbo, 2015).

In many African countries, RV and DEC cause more than half of the gastrointestinal disease burden (Katukiza et al., 2013; Machdar et al., 2013; Mwenda et al., 2010). Our study focuses on Uganda as a representative sub-Saharan country. In Uganda, approximately 7.3% of deaths overall are due to RV infections among children under five years old, and 33 to 45% of all hospitalized cases of diarrhea each year are due to RV (Bwogi et al., 2016; Mwenda et al., 2010; Nakawesi et al., 2010; Sigei et al., 2015). Unlike rural areas, urban centers are emission hotspots characterized by poor sanitation and constant outbreaks of gastrointestinal infections from bacteria, viruses, protozoa, and helminths (Matthys et al., 2007). An epidemiological study done in Kampala, Uganda's capital, estimated diarrheal disease burden from exposure to wastewater pathogens at 304.3 disability-adjusted life years (DALYs), with 59,493 total disease episodes per year (Fuhrimann et al., 2016). The diarrheal disease burden for Kampala was developed in a quantitative microbial risk assessment using observational data of waterborne microorganism concentrations in the surface waters and assumed relations between the observed microorganisms and the pathogens relevant for the disease burden (Fuhrimann et al., 2016).

To better understand the disease burden elsewhere and to study the impact of population growth, socioeconomic development, and sanitation changes on the disease burden, more observational data would be required. Observational microorganism and pathogen concentration data are often sparse. However, integrating environmental loads modeling with hydrology could enable the simulation of waterborne pathogen concentrations. These simulated concentrations can then be used in quantitative microbial risk assessments to determine health risks and burden of disease and to identify high burden areas (hotspots). Additionally, this modeling framework can be used to better understand the impact of management implications, such as improved wastewater treatment, and enable scenario analysis of future changes to the burden of disease due to waterborne pathogens like RV and DEC. Such a modeling framework contributes to the better understanding required for achieving the United Nations Sustainable Development Goals (United Nations, 2015).

As a first step in developing a loads–concentrations–risk–burden of disease framework, a loads model should be developed to estimate the emissions of RV and EC to surface water. An example of such a model at the global scale is the Global Waterborne Pathogen model for human RV emissions, version 1 (GloWPa-Rota H1; Kiulia et al., 2015), which has been applied to India and Bangladesh for Cryptosporidium (Vermeulen et al., 2015). However, such a model has not been applied to African countries. In our study, the GloWPa-Rota H1 model (herein written as GloWPa-H1) was downscaled to study RV and EC emissions from various sanitation systems to surface water in Uganda. The GloWPa-H1 model excludes emissions from pit latrines and septic tanks, yet a large proportion of Uganda's population uses onsite sanitation systems. Williams and Overbo (2015) showed that not all feces from onsite sanitation are safely contained, as was assumed for the GloWPa-H1 model. Therefore, we developed the new Kampala Waterborne Pathogen model for human RV and EC emissions (KlaWPa-H1) (see section "A New Approach: The KlaWPa-H1 Model" below) that includes pit latrine and septic tank emissions into the loads, using a shit flow diagram (SFD) (Schoebitz et al., 2016). Due to lack of nationwide data, the KlaWPa-H1 model was developed for Kampala only. The SFD used estimates emissions to the environment instead of the surface water. Thus, while the GloWPa-H1 model is expected to produce low-end loads, the KlaWPa-H1 model is expected to produce higher loads to the surface water.

The objective of our study was to analyze current and future RV and EC emissions to the surface water using the GloWPa-H1 and KlaWPa-H1 models, to understand the contribution of onsite sanitation systems as a proportion of the total emissions and to evaluate opportunities to model emissions at country scale. We applied the models to Uganda and Kampala respectively, as an example of a country and a city where a large share of the population uses onsite sanitation. This approach can be applied elsewhere because both models use generic input data available in other countries.

METHODS

Two models were used to estimate RV and EC emissions for the study areas, Uganda and Kampala, for the baseline year 2015 and for different sanitation management scenarios in 2030.

Study Area

The GloWPa-H1 model was applied to Uganda, whereas the KlaWPa-H1 model was developed for Kampala. Covering a total surface area of 241,551 km^2, Uganda is located astride the equator in East Africa. In the 2014 national census, the country's population was estimated to be 34.6 million persons. Uganda has 111 administrative districts with one city. Kampala is the most populous urban center, with a population of over 1.5 million persons (UBOS, 2014).

Uganda failed to meet the 2015 millennium development goals target for access to improved sanitation (WHO/UNICEF, 2015), with only 29% of the urban and 17% of the rural populations having access to improved sanitation. Between 1990 and 2015, Uganda added other unimproved sanitation facilities, while open defecation remained in rural areas. The Ministry of Water and Environment data for coverage of onsite facilities is relatively higher, at over 90%, because shared facilities are included (MWE, 2016). Moreover, only a few urban areas are connected to sewers, with a coverage of 7% (1% nationwide). With an annual urbanization of 5% (World Bank, 2015), sanitation infrastructure has not matched urban population growth, making sanitation challenges more prevalent, mainly for the poor people in urban areas.

Adequate wastewater treatment has high removal efficiency for both RV and EC (Williams and Overbo, 2015). Uganda uses more wastewater stabilization ponds (WSPs) than conventional wastewater treatment plants (CWTPs), with the latter installed up to the secondary stage. Multistage WSPs can remove up to 99% of RV particles through anaerobic, facultative, and maturation ponds. Both CWTPs and WSPs remove 95 to 99% of viruses and bacteria through multiple stages (Fair et al., 1970; Ghazy et al., 2008; Rowe and Abdel-Magid, 1995; Williams and Overbo, 2015). However, adequate wastewater treatment is lacking in the country and is heightened by low fecal sludge collection. Extensive use of onsite facilities (pit latrines) and the low return on investment of sewers limit sewerage expansion (Fuhrimann et al., 2016; MWE, 2016; NWSC, 2016; World Bank, 2010). Still, the government-owned water and wastewater utility, National Water and Sewerage Corporation (NWSC), plans to increase coverage from 7 to 30% in operational districts by 2021 (NWSC, 2016).

The GloWPa-H1 Model

We used the GloWPa-Rota H1 model (Kiulia et al., 2015) and a replicate GloWPa-Ecoli H1 model to estimate respective human RV and EC emissions to surface water. The GloWPa-H1 model was applied at a denser resolution than the standard 0.5 × 0.5° latitude × longitude. Three emission categories are identified: (i) connected emissions from sewerage reaching surface water directly or after treatment, (ii) direct emissions from the population with hanging toilets and the urban population practicing open defecation, and (iii) diffuse emissions from the rural population practicing open defecation. In the GloWPa-H1 model, pit latrines and septic tanks are non-sources of emissions because feces were assumedly safely contained and with die-off over long-term storage meaning that no pathogens reach the surface water. Calculations depend on RV and EC incidence and excretion rates, district urban and rural population data, age-grouping, sanitation types and coverage, and wastewater treatment. Unlike in Kiulia et al. (2015), our account of the model computes emissions from both CWTPs and WSPs considering treated waste fractions, removal efficacies, and nontreatment. The model estimates average daily total RV particles and EC CFU for each district. Per capita emissions from the urban and rural population were distributed on a LandScan2010 (adjusted to 2015) population density map (Bright et al., 2011), at a 0.5-min resolution (0.00833 × 0.00833° latitude × longitude, approximately 1-km^2 grids). Table 1 lists parameters and values for baseline conditions and scenarios. Table 2 provides values for the population and country averages for sanitation and wastewater treatment fractions.

A New Approach: The KlaWPa-H1 Model

The GloWPa-H1 model excludes pit latrines and septic tanks emissions, consequently producing low-end emissions since feces from pit latrines and septic tanks often end up in the surface water (Williams and Overbo, 2015). Therefore, we developed a new model, the Kampala Water Pathogens model for human RV and EC emissions (KlaWPa-H1), to add those emissions. Using a different approach, the KlaWPa-H1 exploits SFD data for Kampala (Schoebitz et al., 2016). The SFD identifies safely and unsafely managed waste fractions during containment, emptying, transport, and treatment. Sanitation types were grouped into sewerage (offsite), fecal sludge contained onsite (onsite-contained), fecal sludge not contained onsite (onsite-not-contained), and open defecation (Table 3). Like the GlowPa-H1 model, the KlaWPa-H1 model uses RV and EC excretion, incidence rates, and removal efficiencies during wastewater treatment (Table 1). While unable to identify where the unsafely managed waste ends up, we assumed that all unsafely managed wastewater reaches the surface water. However, this should be a high-end estimation since feces may be spread on land or enter groundwater instead. Emissions for the KlaWPa-H1 model are average daily total emissions for Kampala, approximately for the year 2015. The model's equations are provided in Supplemental Material 1.

Sensitivity Analysis

A sensitivity analysis was performed for the GloWPa-H1 model in Vermeulen et al. (2015). The study investigated how modeled output varies with changes in 10 input variables, with each variable taking up to three values. In the current study, we conducted a sensitivity analysis for the KlaWPa-H1 model following the approach in Vermeulen et al. (2015). We studied how modeled RV emissions output varied with changes in input variables. These variables include RV incidences for children under five years old and for others versus RV excretion rates, and proportions of Kampala's treated fecal waste versus treatment type and removal stage efficacies. A total of 18 runs were made for each pair of parameters in different combinations. Values were assorted into low, medium, or high compared with the standard run.

Scenario Analysis

We developed future management scenarios for RV and EC emissions of the GloWPa-H1 and KlaWPa-H1 models from three actor-based strategies: (i) the Ministry of Water and Environment sector development plan for the financial year 2019–2020 (MWE, 2016, 2017) to increase onsite sanitation coverage and reach 100% coverage in small towns and rural growth areas, and the Ministry of Health's Uganda Sanitation Fund Program to improve access to basic onsite sanitation, promote household hygiene, and end open defecation (Global Sanitation Fund, 2017); (ii) NWSC's 5-yr plan to improve sewer coverage from 7 to 30% in their districts of operation between 2016 and 2021 (NWSC, 2016) and comply with treatment effluent discharge standards; and (iii) the UN 2015 SDG resolution 6.3 on halving untreated wastewater by 2030 (United Nations, 2015). Table 2 shows baseline conditions (BS) in 2015 and scenario descriptions for 2030: S1 is "Business as Usual," S2 is "Industrious," and S3 is "Low Emissions." Changes in population, sanitation, and wastewater treatment are developed based on the actor-based strategies. These changes include population growth, increased urban and rural coverage of improved sanitation, RV and EC treatment removal efficiency, and addition of tertiary treatment to CWTPs. We adjusted the LandScan2010 gridded data to scenario urban and rural population projections for 2030 to enable production of emission maps for the GloWPa-H1 model. In both models, our main assumptions concern S3. Instead of NWSC's 30% target in 2021, we use a 20% sewerage coverage in 2030 because (i) NWSC's 6-yr growth trend has remained at 6.5% since 2011 and (ii) the 20% coverage appears more feasible for 2030 than NWSC's 30% for 2021. Other assumptions are that in 2030 urban and rural grids remain urban or rural, respectively, that all gridded district populations grow at equal proportions from the baseline, that the wastewater treatment efficiency for the different stages is not improved, and that a zero-mobilization potential is used for the onsite-contained and not emptied category.

RESULTS

Sensitivity Analysis

In Vermeulen et al. (2015), the most sensitive parameters were excretion and incidence of *Cryptosporidium* in the study populations, producing up to a 20-fold increase in emissions, with a 1 $\log_{10}$ increase in excretion and doubling of incidence rates. Similarly, the most sensitive parameters in the KlaWPa-H1 model were RV excretion and infection rates. Doubling the incidence in children under five years old to 48%, increasing the incidence in others to 10%, and raising the excretion rate to 1×10^{12} particles per capita increases RV emissions from the standard 14.57 $\log_{10}$ particles d^{-1} to 17.30 $\log_{10}$ particles d^{-1}. This is equivalent to a 2 $\log_{10}$ increase from excretion and 0.73 log increase from incidence. Increasing the fractions of treated waste versus high corresponding removal efficacies produced a smaller log reduction (0.1 $\log_{10}$). KlaWPa-H1's sensitivity analysis results are provided in Supplemental Material 2.

GloWPa-H1 Results

In 2015, average daily total emissions to surface water were estimated at 6.18×10^{14} RV particles and 1.31×10^{12} EC CFU. Urban emissions were 88 and 89% of total emissions for RV and EC, respectively. Children under five years contributed 82% to the RV emissions total, despite being only 18% of the population. As in Kiulia et al. (2015), high infection rates in children under five years old (Table 1) led to increased RV shedding. On the contrary, total EC emissions from children under five years are only proportional to their population size because we used the same incidence for all ages. Spatial emissions show the same areas with high emissions (hotspots) for RV (Fig. 1, a1) and EC (Fig. 1, a2). Densely populated urban areas in the districts of Kampala, Wakiso, Masaka, Gulu, Arua, Kitgum, Buikwe, Iganga, and Jinja are emission hotspots, with averages of 2.11×10^{13} RV particles d^{-1} and 4.94×10^{10} EC CFU d^{-1}. Low emission districts are Rubirizi, Buhweju, Moyo, Mitooma, and Kaberamaido, with averages of 4.72×10^{11} RV particles d^{-1} and 9.03×10^{8} EC CFU d^{-1}.

For BS, direct RV and EC emissions were 74 and 69% of the totals, respectively, in 2015 (Fig. 2). Direct emissions were from a smaller urban population, that is, 15% of the 2015 national population. Connected RV emissions accounted for 14%, whereas diffuse emissions were 12% of the total. Connected EC emissions were 20%, and diffuse EC emissions 11%. Uganda has only 18 towns with wastewater collection and treatment facilities, serving 7% of the population, but which averages to just 1% nationwide (Table 2). Low sewerage coverage justifies the limited share of connected RV and EC emissions, with Kampala, Wakiso, Jinja, Mbale, and Mbarara as hotspots. Districts with the highest open defecation emissions were Arua, Kotido, Mayuge, Kamuli, Kaabong, and Kibaale. Those emissions come from their large rural populations.

In 2030, the total population is expected to rise by 57%, with 80% being rural and 20% urban. Across scenarios, urban RV and EC emissions are higher than rural emissions, originating from connected and direct sources. For S1, RV emissions will increase by 75% to 1.08×10^{15} particles d^{-1}, whereas EC emissions rise by 91% to 2.50×10^{12} CFU d^{-1}. Kampala and other densely populated districts remain emission hotspots (Fig. 1, b1 and b3). Despite an increase in total emissions, percentage shares from connected, direct, and diffuse emissions are almost equal to BS (Fig. 2). At 80%, urban direct emissions are higher than connected urban (11%) or diffuse rural emissions (9%). Compared with BS, RV emissions will rise by 46% in connected, 87% in direct, and 33% in diffuse sources. The EC emissions will also increase by 60% (connected), 107% (direct), and 47% (diffuse) (Fig. 3). All changes in S1 are solely caused by an increased population in 2030, since sanitation coverage, wastewater treatment, and open defecation are limited to BS levels.

Total emissions are highest in S2 compared with all other scenarios, with 1.93×10^{15} RV particles d^{-1} and 5.63×10^{12} EC CFU d^{-1}. Gridded emissions in c1 and c3 of Fig. 1, are also at their peaks. Compared with BS, emissions in S2 will rise by 212% for RV and 330% for EC. Connected emissions are the largest, at 61% (RV) and 71% (EC), followed by direct emissions with 35% (RV) and 26% (EC) and diffuse emissions at 4% (RV) and 3% (EC) (Fig. 2). Connected RV emissions will increase drastically by 1308%, direct emissions by 48%, and diffuse emissions by 1% (Fig. 3). Both connected and diffuse EC emissions will rise by 1447% and 64% respectively, and direct emissions by 47% (Fig. 3). The overwhelming rise in connected RV and EC emissions is because 50% of the population in the urban and 10% in rural areas of all districts are connected to sewers (Table 2). More feces are mobilized to treatment plants, unlike in BS, S1, or S3. The assumed 50% of feces going to primary treatment and 30% to secondary treatment are insufficient to reduce emissions. Only 4% (RV) and 3% (EC) of the total emissions are from open defecation, contributed by 15% of the total population in 2030 (Table 2, Fig. 2).

S3 has the lowest total emissions of 2.57×10^{14} RV particles d^{-1} and 8.44×10^{11} EC CFU d^{-1}. Compared with BS, total emissions could be expected to fall by 58% (RV) and 36% (EC) by 2030. Direct emissions are eliminated, leaving connected emissions at 91% (RV) and 94% (EC) and diffuse emissions at 9% (RV) and 6% (EC) (Fig. 2). Connected emissions reaching surface water are expected to increase by 180% (RV) and 207% (EC) (Fig. 3) because the total population connected to sewers is higher in S3 than in BS. For both microorganisms, direct emissions are nonexistent because all urban households have sanitation facilities. Diffuse RV and EC emissions are reduced by 66% each because only 5% of the country's population practices open defecation (Table 2, Fig. 3). Emissions in Fig. 1 (d1 and d3) are lowest throughout the country, with negative differences (Fig. 1, d2 and d4) in most districts. A large share of the non-source population (with pit latrines and septic tanks) (Table 2) and eradicated direct or diffuse sources results in reduced emissions, while the large sewered population of Kampala remains a key hotspot (Fig. 1, d1 and d3).

KlaWPa-H1 Results

The KlaWPa-H1 model revealed emissions from pit latrines and septic tanks ignored in the GloWPa-H1 model using Kampala's excreta-flow data. The KlaWPa-H1 model simulates a total of 3.74×10^{14} RV particles d^{-1} and 8.18×10^{11} EC CFU d^{-1} reaching the surface water in Kampala in 2015. Expectedly, onsite-not-contained is the largest contributor, taking 66% of the RV (14.4 $\log_{10}$ units) and 59% of the EC (11.7 $\log_{10}$ units) emissions (Fig. 4). In these sanitation systems, fecal sludge is not stored onsite, but most of it ends up directly or indirectly in the surface water. Offsite emissions are second highest at 19% (RV) and 27% (EC).

Onsite-contained emissions are 13% of RV and 11% of EC total emissions. Children under five years old produce 82% to total RV emissions, while other age groups contribute 18%. The EC emissions are only proportional to age group sizes. High RV excretion rates in infected children under five years old are the result of large emissions, as shown in the GloWPa-H1 model.

Both S1 and S2 have comparable emissions, at 4.80×10^{14} and 4.71×10^{14} RV particles d^{-1} and 1.17×10^{12} and 1.03×10^{12} EC CFU d^{-1}, respectively. In S2, emissions are transferred from onsite-not-contained to offsite (sewerage) sanitation because half of Kampala's population is connected to sewers, reducing the shares of onsite-contained and onsite-not-contained (Table 2). S3 leads to the lowest emissions at 1.11×10^{14} RV particles d^{-1} and 2.65×10^{11} EC CFU d^{-1}, which is a 0.4 $\log_{10}$ units reduction for both organisms. In S3, only 20% of the population is connected to sewers, 86% is safely contained onsite, and 90% of feces not contained onsite are taken to treatment.

Figure 5 shows the change in scenario emissions in 2030 compared with BS. Emissions will generally increase by 0.1 $\log_{10}$ units for both RV and EC in S1 across all categories, due to an increase in population. Despite having the largest share of emissions, S2 will see a slight reduction of onsite-contained and onsite-not-contained emissions simply because total onsite fractions reduce while the sewered population grows. However, 0.4 and 0.1 $\log_{10}$ units of RV and EC will be added, coming from offsite sanitation and open defecation, respectively. The least-polluting scenario is S3, with a total of 1.2 $\log_{10}$ reduction in offsite, onsite-contained, and, the most important category, onsite-not-contained. Low emissions are due to the low sewerage coverage, high wastewater collection and treatment efficiency, more people safely containing their feces onsite. and open defecation being eliminated.

Comparison of the GloWPa-H1 and KlaWPa-H1 Results

We compared total and age-group RV and EC emissions for Kampala in 2015 from the GloWPa-H1 and the KlaWPa-H1 models. Estimated emissions are lower in the GloWPa-H1 model than in the KlaWPa-H1 model, at 5.95×10^{13} RV particles d^{-1}, 1.75×10^{11} EC CFU d^{-1} vs. 3.74×10^{14} RV particles d^{-1}, 8.18×10^{11} EC CFU d^{-1}, respectively. The KlaWPa-H1 model simulates an additional 0.80 (RV) and 0.67 (EC) $\log_{10}$ units from pit latrines and septic tanks (Fig. 6). The KlaWPa-H1 model also highlights waste that does not reach treatment plants from each category except for open defecation. Connected emissions from the KlaWPa-H1 model are slightly higher than corresponding emissions of the GloWPa-H1 model, with an additional 0.15 $\log_{10}$ units for both RV and EC. This difference is due to the lack of synchrony in the treated, untreated, and undelivered fecal fractions between NWSC's sewerage coverage data and Kampala's SFD.

DISCUSSION

In this study, the GloWPa-H1 and KlaWPa-H1 models were used to estimate RV and EC loads to the surface water. The RV and EC annual average daily total emissions to the surface water for Kampala were simulated to be between 5.95×10^{13} and 3.74×10^{14} viral particles d^{-1} and between 1.75×10^{11} and 8.18×10^{11} CFU d^{-1} for the year 2015. As expected, the lowest emissions were simulated with the GloWPa-H1 model because emissions from onsite systems were not included in the model. The highest emissions were simulated with the KlaWPa-H1 model that was expected to provide high-end emissions because it was impossible to remove the land and groundwater emissions from the totals.

The main sources for Kampala emission were people with sewer connections in the GloWPa-H1 model and onsite-not-contained emissions from unsafe pit latrines and septic tanks in the KlaWPa-H1 model. Onsite emissions from the KlaWPa-H1 model are larger than the total emissions for Kampala from the GloWPa-H1 model. The significance of onsite sanitation systems and source attribution are highlighted for future studies.

Uganda has a large share of onsite sanitation (>70%) in urban and rural areas, except for a few districts where open defecation is practiced. The maps produced by the GloWPa-H1 model (Fig. 1), therefore, likely show low emissions. There are also some differences between hotspot areas. Currently, Kampala with its high urban population and with a significant fraction of open defecation is the largest hotspot area. Other densely populated areas with a large share of onsite sanitation could also emerge when onsite systems are included in the GloWPa-H1 model. However, population density remains a main driver for emissions, and it is unlikely that other rural areas become hotspots.

The relative changes in emissions with respect to BS in different scenarios are interesting to analyze and are comparable for both the GloWPa-H1 and KlaWPa-H1 models. The emissions are expected to increase for S1 and S2 and to decrease for S3. The population growth alone increases S1 emissions. When more people are connected to sewers, emissions increase when wastewater treatment is insufficient, as is the case in S2. Finally, the results for S3 show that reductions are possible when emissions from open defecation are eliminated and onsite waste is safely contained or effectively treated.

Undeniably, the GloWPa-H1 and KlaWPa-H1 models have uncertainties in addition to the inclusion of leakages from onsite systems. Validation of modeled emissions would be important, although currently impossible due to limited observational data on wastewater treatment efficacy, effluent concentrations, and onsite system leakages. However, when modeled emissions are integrated with hydrology, the concentrations in the surface water can be validated with measured concentrations. *Cryptosporidium* concentrations simulated with the GloWPa-H1 model have been compared with observational data and showed reasonable results given several assumptions made in this model to estimate livestock emissions, pathogen runoff from the land, and so on, in a case study for Bangladesh and India (Vermeulen, 2018). Simulating concentrations was beyond the scope of this study.

A sensitivity analysis was performed to better understand the influence of the different variables on model output. The most important variable for the GloWPa-H1 (Vermeulen et al., 2015) and KlaWPa-H1 models (Supplemental Material 2) is RV excretion of the population. This excretion rate is based on a literature review performed for the GloWPa-H1 model (Kiulia et al., 2015) and is uncertain since RV incidence rates vary between age groups, healthy or infected individuals, prevalent sanitation conditions, and weather patterns (Bwogi et al., 2016; Fuhrimann et al., 2016; Mwenda et al., 2010). The RV excretion rate we used was not based on Uganda's prevalence data because such data are unavailable. Although halving or doubling standard excretion or incidence rates leads to magnitudinal changes in emissions, we do not expect that this strongly affects the spatial distribution patterns of the emissions. Thus, RV and EC distribution results in emission maps and in the KlaWPa-H1 model are valid. Additionally, obtaining exact values is not relevant for our purpose. Instead, the relative differences between models and scenarios help identify key emission sources, hotspots, and the effects of sanitation changes on emissions. It should be noted, however, that the model results are for the endemic disease, not for outbreaks of the virus.

Although of lower importance according to the sensitivity analysis, other uncertainties in the models include the underlying sanitation data and understanding of the exact removal in the wastewater treatment systems. For instance, observational data by the NWSC places sewer coverage for Kampala at 7.5%, whereas the SFD in Schoebitz et al. (2016) indicates a 22% coverage. The latter was used in our models. In addition, Kampala has a population of 1.5 million people, which often doubles during the day (Kampala Fecal Sludge Management Project, 2016). Such daily changes are not included in our models. Moreover, using RV and EC incidences of BS to estimate emissions in 2030 may not represent future emissions. In 2030, RV and EC incidence will likely change as the country develops and the population increases. Vaccination can also reduce emissions, although ignored in our study. Rotavirus vaccination offers reductions in mortality and morbidity in some developing countries, despite efficacy challenges from the wide variability of circulating strains (Enweronu-Laryea et al., 2014; Fischer Walker and Black, 2011). Finally, we highlight that the models aim to estimate annual average daily total emissions. Undeniably, changes in precipitation affect the actual daily emissions. For instance, several of Kampala's low-lying areas (particularly natural streams, drainage channels, and wetlands), are prone to floods due to encroachment and modification (Fuhrimann et al., 2016; MWE, 2016; Schoebitz et al., 2016), and these floods can flush feces from pit latrines into storm drains when they are not covered (Cissé, 2013; Schoebitz et al., 2016). Those extreme events are not included in our models, although the SFD used for the KlaWPa-H1 model may account for extreme events when estimating fecal losses from onsite systems. Future improvements of the model would include a stochastic approach to better quantify the uncertainties. In addition, extremes such as disease outbreaks or impacts of precipitation changes can later be included using scenarios.

This study is the first to simulate pathogen emissions to surface water for a country in Africa, where pathogen data are sparse. We demonstrate that knowledge of the underlying variables, such as sanitation use and wastewater treatment, enable estimation of emission hotspots and the projection of possible future changes. This study also highlights that the inclusion of onsite sanitation systems into emission models is important. This inclusion is not straightforward because different sanitation systems are managed differently, and illegal disposal of fecal sludge occurs in swamps, quarries, and water bodies (MWE, 2016; Schoebitz et al., 2016). In this paper, we take the opportunity that SFDs provide to include onsite systems in our emission modeling. However, one immediate disadvantage of using SFDs is that they are not readily available countrywide. Moreover, the emissions are currently not separated for land, groundwater, or surface water. To provide maps that include onsite sanitation across Uganda, SFDs that indicate the destination of the feces should become available for all the districts.

Our process-based modeling and scenario approach is a first step toward a framework that links sanitation systems and wastewater treatment to health risks and disease burden. We have demonstrated that connecting more people to sewers (S2) will increase emissions to surface waters. Moreover, eliminating open defecation in urban areas, connecting people to sewers with adequate wastewater treatment, and safe management of fecal waste in onsite systems (S3) will reduce the emissions. In future studies, understanding the effect of scenario emissions on disease burden can close the loop in our loads–concentration–risk modeling framework, aimed at guiding sanitation safety planning.

The sewer coverage in S3 for 2030 is below NWSC's target for 2021. The feasibility of assumptions in S2 and S3 of sewer coverage for all districts in 2030 depends on institutional, legal, and financial capability. Increasing improved onsite sanitation coverage and treatment removal efficiency, reducing nontreatment, and promoting household hygiene are possible short- and long-term-focus areas for the Ministry of Water and Environment, NWSC, and the Ministry of Health. Furthermore, other developed scenarios can be used with the models to enable decision makers to make more-informed decisions for sanitation safety planning. In this way, we contribute toward the attainment of the UN's Sustainable Development Goals 6 and 3.

Conclusions

This study explores how changes in population, sanitation types, and coverage and wastewater treatment affect RV and EC emissions to surface water in Uganda. The GloWPa-H1 model spatially represents emissions for the baseline year 2015 and for scenarios in 2030. The KlaWPa-H1 model represents emissions from all sanitation facilities, including onsite systems. It is a first attempt to include ignored emissions from pit latrines and septic tanks. Both models, however, highlight areas of high emissions to surface water in 2015, their key sources, and the importance of safely managing fecal sludge and adequate wastewater treatment. Overall, connecting more people across scenarios increases emissions, despite removal in wastewater treatment systems. Elimination of open defecation and safe management of onsite systems are indispensable to reduce emissions. Our model- and scenario-based approach can be applied to other countries or regions and empowers decision makers to develop better-informed sanitation plans.

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Table 1. Rotavirus (RV) and *E. coli* (EC) standard model parameters.

Parameter description	Data source
Urban (P_u) and rural (P_r) populations	UBOS, 2014
Population age-group fractions (f_{age}) for <5, 5–14, 15–24, and 25+ years	UBOS, 2014
Excretion rates per gram of feces:	Bishop, 1996
RV: 1.0×10^{10} particles (V_{pRV})	Rowe and Abdel-Magid, 1995
EC: 1.0×10^{6} CFU (CFU_{EC})	Kiulia et al., 2015
Incidence rates:	Campbell and Reece, 2002
RV: 24% in children under 5 years, 1% in others (RV_{in})	
EC: 100% in all people (EC_{in})	
Urban and rural population fractions connected to sewers (f_{cu}, f_{cr}), having direct (f_{du}, f_{dr}), diffuse emissions (f_{difr}), and with CWTP and WSP† treated and untreated fractions (f_t, f_{nt})	MWE (2016); NWSC (2016); Ministry of Health sanitation monitoring data
Run-off fraction (f_{run}) based on animal manure mobilization of 2.5%	Ferguson et al., 2007
RV and EC removal efficacies (RE) for CWTP and WSP treatment:	Kiulia et al., 2015; Williams & Overbo, 2015; NWSC fecal coliforms monitoring data
Primary stage (RE_P): 20.0%	
Secondary stage (RE_S): 97.5%	
Tertiary stage (RE_T): 99.2%	
WSPs (RE_{WSP}): 95%	

† CWTP, conventional wastewater treatment plant; WSP, wastewater stabilization pond.

Table 2. Baseline conditions for the year 2015 and scenario data for the year 2030.

		BS Baseline	S1 Business as Usual	S2 Industrious	S3 Low Emissions
Urban and rural populations (million persons)		34.6	54.5	54.5	54.5
GloWPa-H1 model					
Sanitation coverage					
Sewerage	Urban	1%	1%	50%	20%
	Rural	0%	0%	10%	0%
Onsite sanitation	Urban	75%	75%	40%	80%
	Rural	74%	74%	75%	95%
Open defecation	Urban	25%	25%	10%	0%
	Rural	24%	24%	15%	5%
Wastewater treatment					
Wastewater stabilization ponds		46%	46%	30%	60%
CWTP† primary		1%	1%	20%	60%
CWTP secondary		1%	1%	20%	30%
CWTP tertiary		0%	0%	10%	0%
Nontreatment		52%	52%	20%	10%
KlaWPa-H1 model					
Offsite sanitation (sewerage)		22%	22%	50%	20%
Connected, delivered, treated		36%	36%	40%	90%
Connected, delivered, not treated		23%	23%	20%	5%
Connected, not delivered		41%	41%	40%	5%
Onsite-contained sanitation		38%	38%	30%	70%
Onsite-contained, emptied, delivered, treated		29%	29%	20%	13%
Onsite-contained, emptied, delivered, not treated		5%	5%	7%	1%
Onsite-contained, emptied, not delivered		3%	3%	7%	0%
Onsite-contained, not emptied		63%	63%	66%	86%

Onsite-not-contained sanitation	40%	40%	20%	10%
Onsite-not-contained, emptied, delivered, treated	26%	26%	10%	90%
Onsite-not-contained, emptied, delivered, not treated	8%	8%	5%	10%
Onsite-not-contained, emptied, not delivered	3%	3%	10%	0%
Onsite-not-contained, not emptied	63%	63%	75%	0%
Open defecation	<1%	<1%	<1%	0%

† CWTP, conventional wastewater treatment plant.

Table 3. Categories of emissions from sanitation in SFDs used for the KlaWPa-H1 model.

	Offsite fractions	Onsite-contained fractions for fecal sludge	Onsite-not-contained fractions for fecal sludge	Open defection
Containment	Connected to sewers	Stored onsite	Not stored onsite	Open defecation
Emptying	NA †	Emptied or not emptied	Emptied or not emptied	NA
Transport	Delivered or not delivered to treatment	Delivered or not delivered to treatment	Delivered or not delivered to treatment	NA
Treatment	Treated or not treated	Treated or not treated	Treated or not treated	NA

† NA, Not applicable

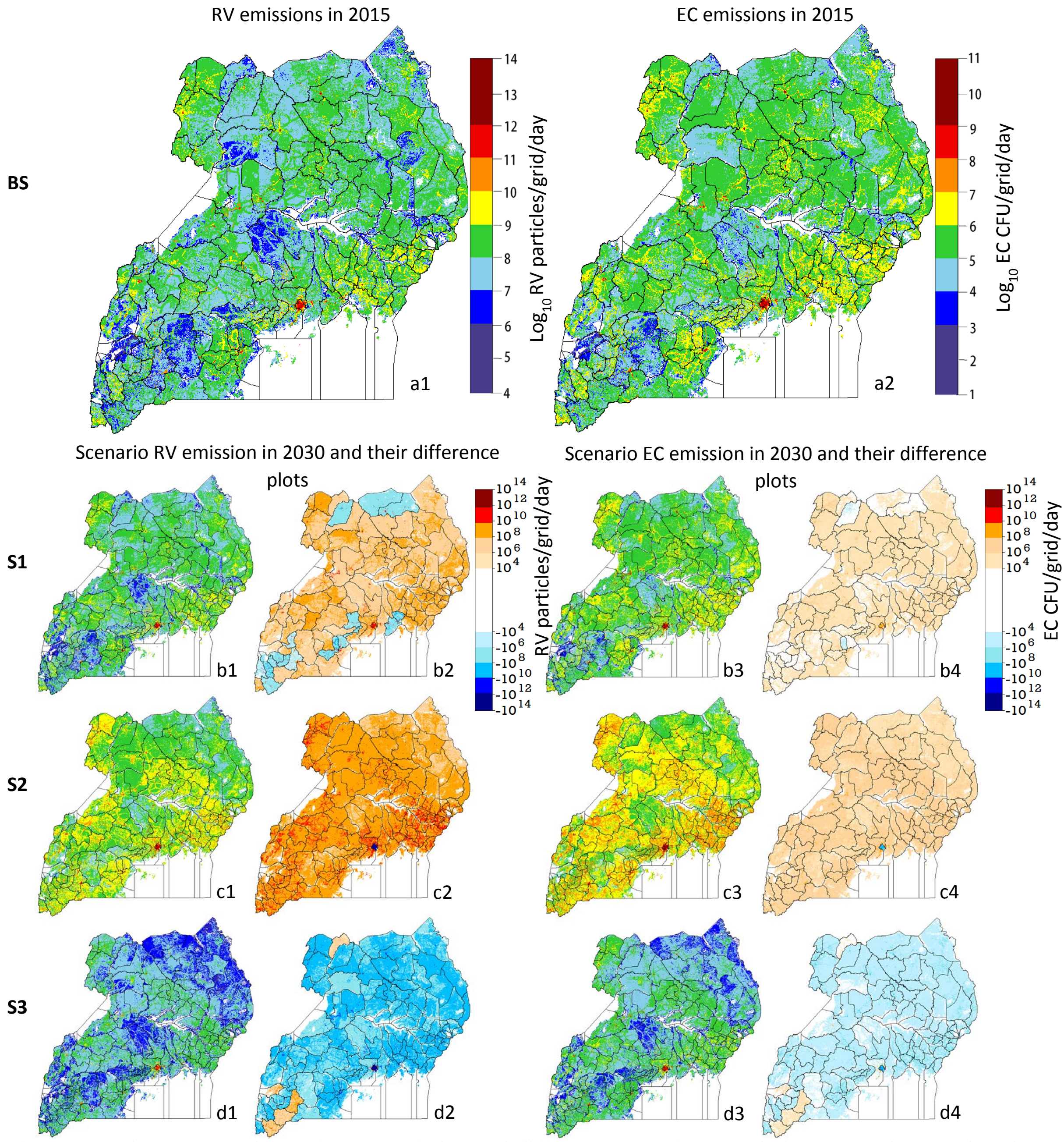
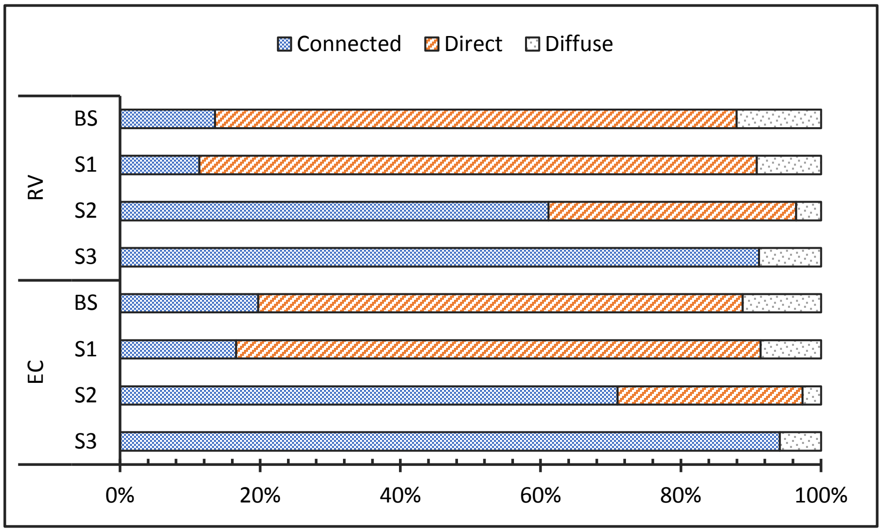
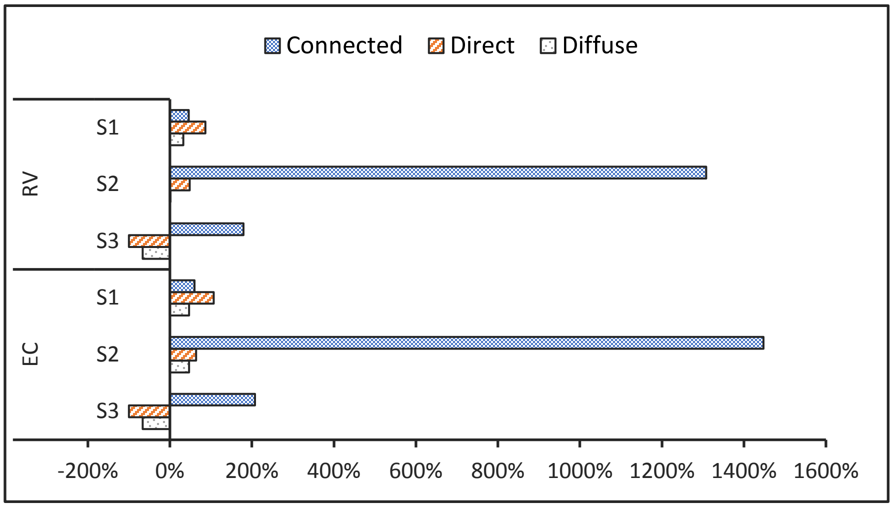


Fig. 1. Rotavirus (RV) and *E. coli* (EC) emission and difference maps for Uganda in 2015 and 2030 plotted on LandScan2010 population density maps adjusted to 2015 for baseline conditions (BS, a) and to scenario populations in Business as Usual (S1, b), Industrious (S2, c), and Low Emissions (S3, d). Populations are distributed into urban and rural grids of approximately 1 km by 1 km. Plots a1–d1 are the standard RV log plots of total district emissions from the baseline to scenarios, with b2–d2 being differences between the respective scenario and the baseline in virus particles per grid per day. Similarly, a2 and b3–d3 are the standard log emission maps for EC with respective difference plots b4–d4 in colony-forming units (CFU) per grid per day.



532 Fig. 2. Share of total emissions from connected, direct and diffuse sources for rotavirus (RV) and *E. coli* (EC) for the baseline (BS) in 2015 and the

533 scenarios (S1, Business as Usual; S2, Industrious; S3, Low Emissions) in



534 Fig. 3. Percentage change in rotavirus (RV) and *E. coli* (EC) emissions for S1 (Business as Usual), S2 (Industrious), and S3 (Low Emissions) in 2030 compared with baseline conditions.

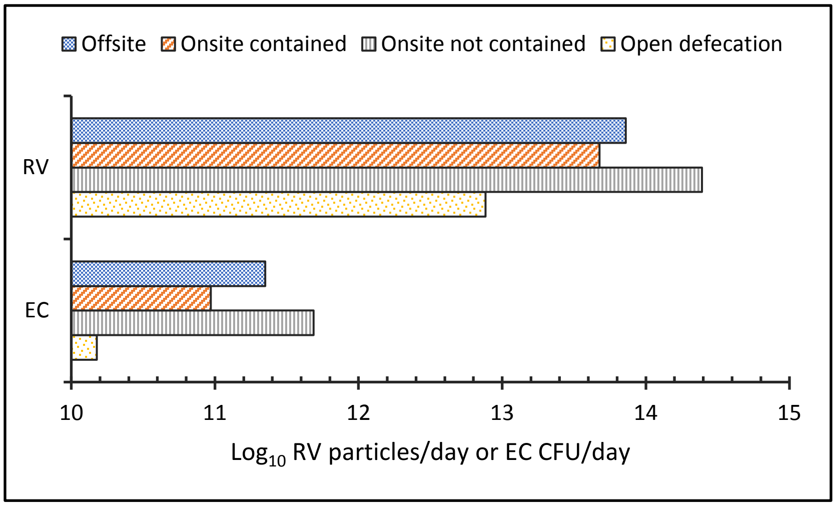


Fig. 4. Kampala's rotavirus (RV) and *E. coli* (EC) emissions in 2015 from sanitation categories of the KlaWPa-H1 model. CFU, colony-

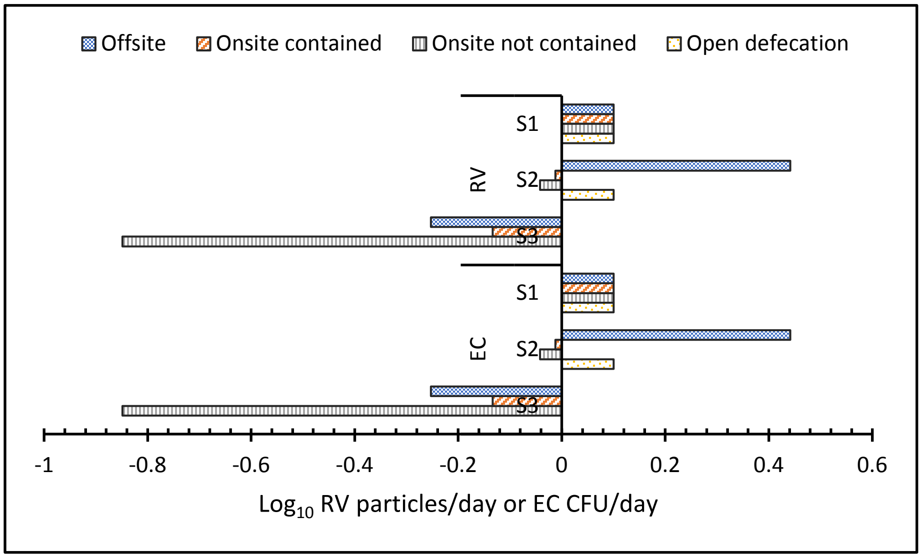


Fig. 5. Change in scenario emissions in the KlaWPa-H1 model in 2030 compared with baseline conditions. CFU, colony-forming units; EC, *E. coli*; RV, rotavirus; S1, Business as Usual; S2, Industrious; S3, Low Emissions.

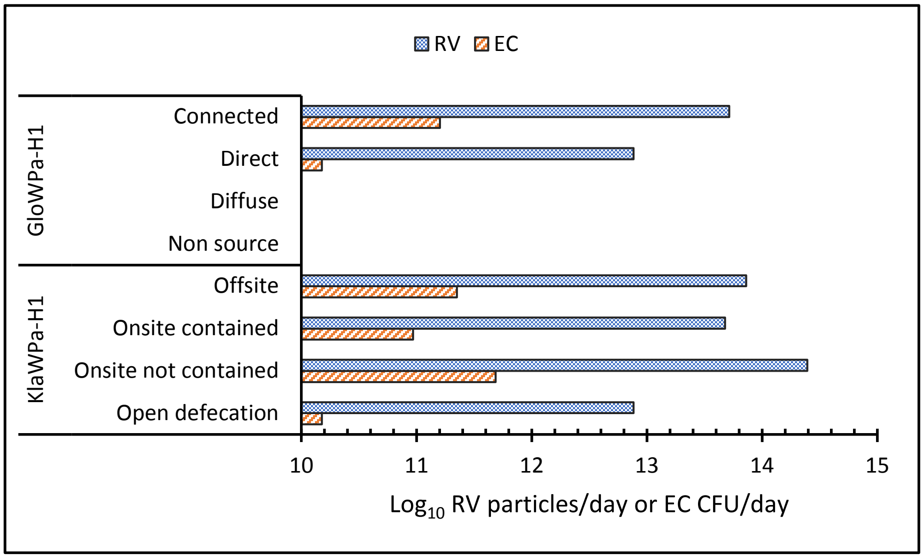


Fig. 6. Comparing rotavirus (RV) and *E. coli* (EC) emissions from the GloWPa-H1 and the KlaWPa-H1 models for Kampala in 2015.

Supplemental Material 1: ***Detailed description of the KlaWPa-H1 model***

The KlaWPa H1 model simulates average daily total RV and EC emissions to the surface water for the district of Kampala for approximately the year 2015. We calculated RV and EC emissions (H) from the base equation:

$$H = P_k x f_{san} x (V_{pRV}\ or\ CFU_{EC})_{ex} x f_{nr} \qquad (1)$$

Where: P_k is the population of Kampala, f_{san} is the population fraction using offsite or onsite sanitation or practicing open defecation, $V_{pRV}\ and\ CFU_{EC}$ are the RV and EC excretion rates and, f_{nr} is the fraction of RV and EC not removed by wastewater treatment.

Emissions categories are given by:

$$Offsite(Of_E) = P_k x f_{age} x (V_{pRV}\ or\ CFU_{EC}) x f_w x [f_{wd} x f_t x (1 - f_{rem}) + f_{wd} x\ f_{nt} + f_{wnd}] \qquad (2)$$

$$Onsite\ contained(Oc_E) = P_k x f_{age} x (V_{pRV}\ or\ CFU_{EC}) x f_s x [f_{se} x f_{sd} x f_t x (1 - f_{rem}) + f_{se} x f_{sd} x f_{nt} + f_{se} x f_{nd} + f_{sne} x p_m] \qquad (3)$$

$$Onsite\ not\ contained(Onc_E) = P_k x f_{age} x (V_{pRV}\ or\ CFU_{EC}) x f_{ns} x [f_{nse} x f_{sd} x f_t x (1 - f_{rem}) + f_{nse} x f_{sd} x f_{nt} + f_{nse} x f_{nd} + f_{nsne}] \qquad (4)$$

$$Open\ defecation(Od_E) = P_k x f_{age} x (V_{pRV}\ or\ CFU_{EC}) x f_{od} \qquad (5)$$

The total RV and EC emissions (H) becomes:

$$H = Of_E + Oc_E + Onc_E + Od_E \qquad (6)$$

For offsite fractions: f_w is sewered wastewater, f_{wd} is sewage delivered to treatment, f_{wnd} is sewage not delivered to treatment, f_t is treated and f_{nt} does not receive treatment. For fecal sludge fractions in onsite-contained and onsite-not-contained emissions: f_s is stored, f_{ns} is not stored onsite, f_{se} is stored and emptied, f_{sne} is stored and not emptied (this is assumed to have a zero mobilization potential - p_m, and remains safely contained), f_{nse} is not stored but is emptied, f_{nsne} is not stored and not emptied, f_{sd} is delivered to treatment, f_{nd} is not delivered to treatment, f_t receives treatment and f_{nt} does not receive treatment. The fraction of open defecation is f_{od}. Fractions for age groups: 0 to <5, 5 to 14, 15 to 24 and 25+ are indicated as f_{age}. The SFD parameters and their values are provided in Table S1, which is an extended version of Table 2. Lastly, f_{rem} is the removal fraction of wastewater treatment for RV and EC. This is computed for each type and stage of treatment as:

$$f_{rem} = f_P\ x\ RE_P + f_S\ x\ RE_S + f_T\ x\ RE_T + f_{WSP}\ x\ RE_{WSP} \qquad (7)$$

Where: f_P, f_S, and f_T are the fractions of CWTPs having primary, secondary and tertiary stages with corresponding RV and EC removal efficiencies: RE_P, RE_S and RE_T respectively. While f_{WSP} and RE_{WSP} are the fractions of WSPs with respective RV and EC removal efficiencies.

Supplemental Material 2: *Sensitivity analysis results for the KlaWPa-H1 model*

Table S1*: Model parameter values for the standard run and the sensitivity analysis runs for RV in the KlaWPa-H1 model*

	Standard values	**Value 1**		**Value 2**		**Value 3**	
Excretion	1E+10	low	1E+08	standard	1E+10	high	1E+12
Incidence in <5-years	0.24	half	0.12	half	0.12	double	0.48
Infection in others	0.01	standard	0.01	high	0.2	high	0.2
RE_{WSP}	0.95	low	0.2	medium	0.4	high	0.99
RE_P	0.2	low	0.2	medium	0.4	standard	0.95
RE_S	0.975	low	0.2	medium	0.4	high	0.99
RE_T	0.9921	low	0.2	medium	0.4	standard	0.9921
Fracion of feces to WSPs	0.3333	high	0.9	medium	0.2	low	0
Fraction of feces to CWTs primary	0.3333	low	0.0333	medium	0.2	high	0.45
Fraction of feces to CWTs secondary	0.3333	low	0.0333	medium	0.2	high	0.45
Fraction of feces to CWTs tertiary	0	low	0.0333	high	0.4	low	0.1

Table S2*: Change in RV emissions for the KlaWPa-H1 model for the different combination of parameter values (in particles/day)*

(See Table S1 for V1, V2, V3)					
Excretion vs Infection rates					
V1 and V1: low excretion vs half incidence in <5, standard incidence in others		**V1 and V2: low excretion vs half incidence in <5, high incidence in others**		**V1 and V3: low excretion vs high incidence in <5, high incidence in others**	
Offsite	3.63E+11	Offsite	7.26E+11	Offsite	5.10E+12
Onsite-contained	2.38E+11	Onsite-contained	4.75E+11	Onsite-contained	2.34E+12
Onsite-not-contained	1.23E+12	Onsite-not-contained	2.46E+12	Onsite-not-contained	1.21E+13
Open defecation	3.83E+10	Open defecation	7.65E+10	Open defecation	3.76E+11
<5	1.53E+12	<5	3.05E+12	<5	6.10E+12
Others	3.46E+11	Others	6.91E+11	Others	1.38E+13

V2 and V1: standard excretion vs low incidence in <5, standard incidence in others		**V2 and V2: standard excretion vs half incidence in <5, high incidence in others**		**V2 and V3: standard excretion vs high incidence in <5, high incidence in others**	
Offsite	3.63E+13	Offsite	7.26E+13	Offsite	5.10E+14
Onsite-contained	2.38E+13	Onsite-contained	4.75E+13	Onsite-contained	2.34E+14
Onsite-not-contained	1.23E+14	Onsite-not-contained	2.46E+14	Onsite-not-contained	1.21E+15
Open defecation	3.83E+12	Open defecation	7.65E+12	Open defecation	3.76E+13
<5	1.53E+14	<5	3.05E+14	<5	6.10E+14
Others	3.46E+13	Others	6.91E+13	Others	1.38E+15
V3 and V1: high excretion vs half incidence in <5, standard incidence in others		**V3 and V2: high excretion vs half incidence in <5, high incidence in others**		**V3 and V3: high excretion vs high incidence in <5, high incidence in others**	
Offsite	3.63E+15	Offsite	7.26E+15	Offsite	5.10E+16
Onsite-contained	2.38E+15	Onsite-contained	4.75E+15	Onsite-contained	2.34E+16
Onsite-not-contained	1.23E+16	Onsite-not-contained	2.46E+16	Onsite-not-contained	1.21E+17
Open defecation	3.83E+14	Open defecation	7.65E+14	Open defecation	3.76E+15
<5	1.53E+16	<5	3.05E+16	<5	6.10E+16
Others	3.46E+15	Others	6.91E+15	Others	1.38E+17
Fraction of treatment systems vs removal efficiencies					
V1 and V1: low CWTPs, more WSPs vs low removal		**V1 and V2: low CWTPs, more WSPs vs average removal**		**V1 and V3: low CWTPs, more WSPs vs high removal**	
Offsite	9.07E+13	Offsite	8.36E+13	Offsite	6.26E+13
Offsite	9.03E+13	Onsite-contained	7.35E+13	Onsite-contained	2.39E+13
Onsite-contained	2.89E+14	Onsite-not-contained	2.72E+14	Onsite-not-contained	2.23E+14
Onsite-not-contained	7.65E+12	Open defecation	7.65E+12	Open defecation	7.65E+12
Open defecation	3.90E+14	<5	3.57E+14	<5	2.58E+14
<5	8.80E+13	Others	8.06E+13	Others	5.87E+13
V2 and V1: medium coverage for other treatment types, high tertiary treatment vs low removal		V2 and V2: medium coverage for other treatment types, high tertiary treatment vs medium removal		V2 and V3: medium coverage for other treatment types, high tertiary treatment vs high removal	
Offsite	9.07E+13	Offsite	8.36E+13	Offsite	6.29E+13

Onsite-contained	9.03E+13	Onsite-contained	7.35E+13	Onsite-contained	2.44E+13
Onsite-not-contained	2.89E+14	Onsite-not-contained	2.72E+14	Onsite-not-contained	2.23E+14
Open defecation	7.65E+12	Open defecation	7.65E+12	Open defecation	7.65E+12
<5	3.90E+14	<5	3.57E+14	<5	2.59E+14
Others	8.80E+13	Others	8.06E+13	Others	5.89E+13
V3 and V1: low WSPs, high primary & secondary, low tertiary treatment vs low removal		**V3 and V2: low WSPs, high primary & secondary, low tertiary treatment vs medium removal**		**V3 and V3: low WSPs, high primary & secondary, low tertiary treatment vs high removal**	
Offsite	9.07E+13	Offsite	8.36E+13	Offsite	6.32E+13
Onsite-contained	9.03E+13	Onsite-contained	7.35E+13	Onsite-contained	2.53E+13
Onsite-not-contained	2.89E+14	Onsite-not-contained	2.72E+14	Onsite-not-contained	2.24E+14
Open defecation	7.65E+12	Open defecation	7.65E+12	Open defecation	7.65E+12
<5	3.90E+14	<5	3.57E+14	<5	2.61E+14
Others	8.80E+13	Others	8.06E+13	Others	5.93E+13