Tools for a comprehensive assessment of public health risks associated with limited sanitation services provision

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Abstract
Three water, sanitation and hygiene (WASH) support tools were applied to Kampala city, Uganda, to evaluate areas with the highest health hazard due to poor wastewater and faecal sludge management and to develop interventions to improve sanitation and reduce exposure. The Pathogen Flow and Mapping Tool (PFMT) assessed how different sanitation management interventions influence pathogen emissions to surface water using rotavirus as the indicator pathogen, while the HyCRISTAL health hazard tool evaluated how flooding and drainage infrastructure influence the presence of human excreta in the environment. The SaniPath tool identified common high-risk pathways of exposure to faecal contamination in food, open drains and floodwater. An overlap in high health hazard hotspot areas was identified by the PFMT and the HyCRISTAL tools. Across the city, the most important hazard sources were the indiscriminate disposal of faecal waste into open stormwater drains from onsite sanitation technologies, open defecation and the insufficient treatment of wastewater. The SaniPath tool identified drain water, floodwater, street food and uncooked produce as the dominant faecal exposure pathways for selected parishes in the city, demonstrating the presence of excreta in the environment. Together, the tools provide collective evidence guiding household, community, and city-wide sanitation, hygiene and infrastructure management interventions from a richer assessment than when a single tool is applied. For areas with high spatial risks, those practising open defecation, and for low-lying areas, these interventions include the provision of watertight pit latrines or septic tanks that are safely managed and regularly emptied. Faecal sludge should be emptied before flood events, direct connections of latrines to open storm drains should be prevented, and the safe handling of food and water promoted. The tools enhance decision making for local authorities, and the assessments can be replicated in other cities.

Keywords
Sanitation, risk assessment, decision support tools, water quality

Introduction

Globally, the burden of enteric diseases is still a major public health concern, particularly in densely populated informal urban settlements characterised by poor sanitation and hygiene (Bwire et al., 2013; Ssemugabo et al., 2019; Szálkai, 2019). Children under 5 years in developing countries are the most vulnerable, contributing 297,000 WASH (water, sanitation and hygiene) attributable deaths and 5.3% of overall deaths in 2016 (Prüss-Ustün et al., 2019).

Enteric pathogens can reach the environment through open defecation, inadequate or lack of wastewater and faecal sludge treatment, leakages, bypass or overflow of untreated waste, flooding in onsite sanitation technologies (pit latrines and septic tanks) and indiscriminate excreta disposal commonly through direct connections to stormwater drains (Peal et al., 2020). Exposure to faecal pathogens in the environment occurs via multiple pathways involving direct contact with faecal matter and the ingestion of, or contact with, contaminated soil, food or water (Eisenberg et al., 2001; Hunter, 2003).

With the onset of climate change, extreme rainfall events are expected to occur more frequently (IPCC, 2013), and may influence enteric disease prevalence. In urban slums, pluvial floods can become a critical climate force that affects the already stressed water and sanitation service delivery systems. The floods can damage infrastructure, mobilise human excreta and clog open drains with solid waste, increasing microbial introduction into the environment and exposure risk to local populations (Braun and Aßheuer, 2011; Dawson et al., 2008; Nkwunonwo et al., 2020).

Slow and unequal progress towards the United Nations Sustainable Development Goal (SDG) 6 for improving universal access to clean water and sanitation by 2030 has been observed in many low-income countries (UNICEF and WHO, 2019). Thus, targeted WASH interventions may require a multifaceted linkage of numerous social-cultural, economic, political, environmental and technical factors. These include the type of sanitation technologies, their functional coverage, policy and governance, financing, cultural orientation, urbanisation trends and the predominant climate (Rose et al., 2019). The World Health Organisation (WHO) has developed guidelines for the safe use of wastewater, excreta and greywater by introducing a risk-based approach known as Sanitation Safety Planning (SSP) (WHO, 2016; Winkler et al., 2017).

The user and site-specific sanitation needs are influenced by population demographics (gender, age and disability), settings like markets and schools, and other public institutions (Larsen et al., 2016). For instance, strengthening the collection and treatment of faecal sludge in densely populated urban areas or temporary population concentration sites with a large onsite technology usage is crucial to curb indiscriminate excreta disposal. Centralised systems with water-based toilets may not be viable options for such areas. However, the expansion of time and resource-intensive centralised systems remains a focus of most local sanitation actors, often only benefiting small non-poor urban populations (Schrecongost et al., 2020).

Integrating sanitation management interventions into diverging urban development planning needs can trigger multiple benefits, including improved environmental quality, better public health, and enhanced livelihood and productivity (Labite et al., 2010; Scott et al., 2019). City-Wide Inclusive Sanitation (CWIS) is a recent campaign towards equitably meeting diverging population needs under urban development planning, by bringing together different actors and stakeholders, while focusing on achieving SDG6 sanitation targets (Schrecongost et al., 2020; Scott et al., 2019).

SDG6 extends beyond infrastructure-based outcomes and requires the measurement of service-based outputs. Furthermore, the collective integration of WHO's SSPs can help practitioners prioritise on risk-based interventions for managing sanitation and use of wastewater, excreta and greywater in a stepwise manner (WHO, 2017). Sanitation coverage alone may not be effective without essential services like safe faecal sludge emptying, collection, and treatment, and good hygiene practices. As service-level performance indicators, access to hand washing and safe faecal sludge management should ultimately correlate with improved public health and quality of life (Schrecongost et al., 2020; Winkler et al., 2017).

The Kampala Capital City Authority (KCCA) in Kampala, Uganda, is committed to improving WASH services, including the safe management of faecal sludge and sewerage across the city (Salian et al., 2020). Extensive household sanitation survey data were previously collected by

KCCA, to inform their WASH-related decisions (Musabe, 2017). This data and the several previous sanitation and health-related water microbiology studies (Fuhrimann et al., 2016a; Katukiza et al., 2010; Kwiringira et al., 2014; Murungi and Van Dijk, 2014; Schneeberger et al., 2019; Schoebitz et al., 2016, 2017) make Kampala a compelling case study. KCCA developed sanitation and hygiene-related questions to be addressed at household, community and city scale, including:

(a) What areas of the city are predicted to have the highest health hazard?
(b) Which interventions can reduce health risks from excreta in the environment involving sanitation technologies use and behaviour change?

The background to this study originates from an unanswered question raised by Schrecongost et al. (2020) on the implications of CWIS for policy and practice. It involves how to identify and categorise dominant sanitation challenges and prioritising interventions that bring (stepwise) public health benefits to specific populations. To address these questions, our paper uses three complimentary WASH assessment tools briefly introduced below and presented in Sections S1, S2 and S3 of the Supplementary Material (S).

Methods: Case study area, assessment tools and models used

Background to the case study area: Kampala city

Kampala is a fast-growing city with about 1.68 (2019) million residents and 2–3 million day-transient people (Salian et al., 2020; Schneeberger et al., 2019), seated at 1190 metres above sea level northward of Lake Victoria in Uganda. The high urbanisation rate, population growth and the rapid expansion of informal settlements have induced enormous pressure beyond the capacity and resources for KCCA to provide equitable access to safe sanitation for resident and transient populations (Schneeberger et al., 2019; Schoebitz et al., 2016). Onsite sanitation technologies are dominant (covering 90%), while sewerage and treatment infrastructure are overloaded, yet only serving a fraction of the central business district and surrounding areas, which hosts most of the day-transient population (Fuhrimann et al., 2014; Schoebitz et al., 2016).

The high water table in low-lying areas means that only shallow pit latrines can be constructed, yet they have limited capacity, fill up rapidly, and therefore require frequent faecal sludge emptying (Murungi and Van Dijk, 2014). Such facilities are more prone to flooding and can lead to contamination of groundwater. KCCA allows mechanised (vacuum trucks) and semi-mechanised (gulpers) faecal sludge emptying, while informal operations are not recommended and are largely undocumented (Schoebitz et al., 2016). This means that faecal sludge emptied informally through manual mechanisms, may not reach treatment facilities. It may be dumped illegally into open stormwater drains, buried onsite or the facility is abandoned (Schoebitz et al., 2016).

Moreover, solid waste often disposed into pit latrines or stormwater drains can make emptying difficult and block stormwater channels (Katukiza et al., 2012; Schoebitz et al., 2016). Thus, stormwater drains in low-lying and wetland areas of Kampala can contain both faecal, solid and other waste streams containing microbial and chemical hazards, posing widespread health risks to resident communities, sanitation workers and downstream farmers (Fuhrimann et al., 2014, 2016b).

According to KCCA's survey data, approximately 4.9% of the population in Kampala is connected to centralised sewer systems (Supplementary Table S2), which convey wastewater to two treatment plants: the Bugolobi Sewage Works (an activated sludge and trickling filter system) and the Lubigi Wastewater Treatment Plant (stabilisation ponds). Faecal sludge is collected from approximately 23.9% of onsite facilities (Supplementary Table S2) and is transported to the two treatment plants.

The reuse of treated wastewater is often practised through wetland farming of yams, sugar cane and vegetables, while at the treatment plants, faecal sludge is dried and the resulting biosolids sold to farmers mostly outside Kampala (Fuhrimann et al., 2016b; McConville et al., 2019). Previous studies on Kampala's Nakivubo and Bwaise wetlands found significant microbial contamination with faecal origins (Fuhrimann et al., 2014, 2015, 2016a; Katukiza et al., 2014). High exposure risks to parasitic infections, skin and eye diseases and diarrhoea were also found among farmers, slum dwellers and sanitation workers along the Nakivubo wetland, with mean concentrations of up to 2.9×10^5 thermotolerant coliforms, 9.9×10^4 *Escherichia coli* and 1.4×10^2 *Salmonella species* Colony Forming Units (CFU)/100 mL (Fuhrimann et al., 2014, 2015). *E. coli* concentrations had exceeded the WHO thresholds for unrestricted irrigation of crops eaten raw (WHO, 2006).

Assessment tools and models

We present a case study for Kampala, Uganda, utilising three complementary assessment tools, the Pathogen Flow and Mapping Tool (https://tools.waterpathogens.org/maps), SaniPath (https://sanipath.org) and HyCRISTAL. The Pathogen Flow and Mapping Tool (PFMT) predicts the flow of pathogens through onsite and centralised sanitation technologies. The different PFMT processes presented in Figure 1, involving faecal waste containment, emptying, transportation, treatment and disposal, are integrated while identifying both the solid and liquid phases. However,

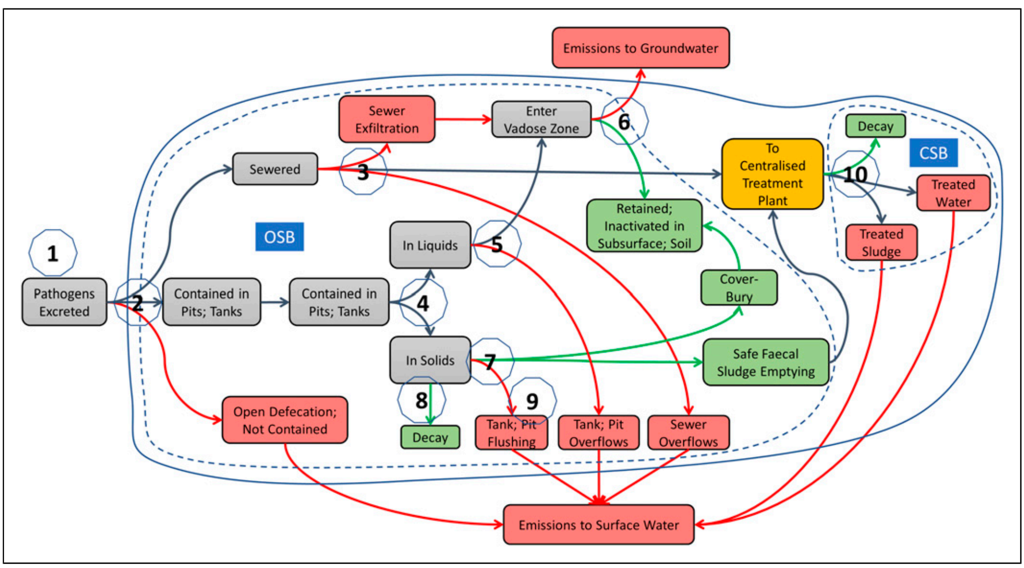

Figure 1. Pathogens flow through the onsite sanitation boundary and the centralised sanitation boundary. The grey, green and red arrows indicate standard, safe or unsafe pathways, respectively. Pathogens are: (1) excreted; (2) initially contained; (3) conveyed by sewerage and emitted via sewerage leaks, overflows or exfiltration; (4) associated with onsite technologies liquid or solid waste fractions; (5) in the liquid fractions of septage and emitted to the vadose zone via leach fields or to surface water when leach fields are absent; (6) emitted to groundwater or retained/inactivated in the subsurface; (7) present in solid faecal sludge or septage and emptied to treatment, covered and buried, or emitted to surface water; (8) decayed in onsite pits or tanks; (9) informally flushed from the solid onsite fraction to surface water and (10) at centralised treatment plants and are inactivated or discharged to surface water in liquid effluent or sludge/biosolids. In this paper, only predicted emission pathways to surface water are included and are adapted from Musaazi (2020).

only the emissions output to surface water are presented in this paper. The HyCRISTAL tool maps health risks associated with infrastructural challenges while factoring associated climate impacts by combining a flood model for flood characteristics and a faecal waste contribution model. Figure 2 shows detailed HyCRISTAL tool features. Finally, the SaniPath tool collects behavioural and microbial concentrations data to profile high health-risk faecal exposure pathways from simulated environmental contamination, exposure frequency, mean exposure and population exposure proportions, as shown in Figure 3. In this paper, the tools collectively identify critical interventions areas to reduce health risks at household, community and city-scale levels. They answer KCCA's

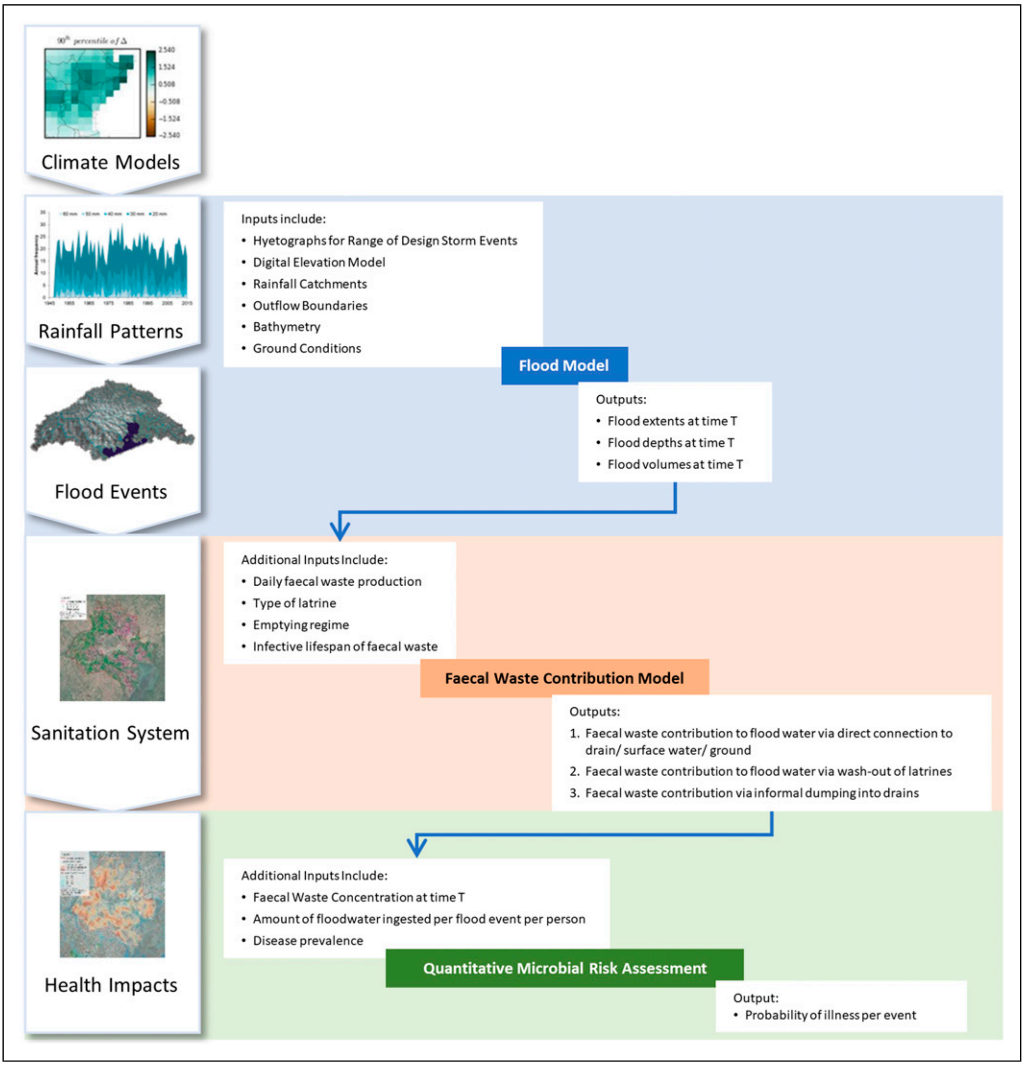

Figure 2. The HyCRISTAL health hazard model comprises of: (1) a flood model which combines various hydrological input data and outputs such as flood extents, flood depths and flood volumes; (2) a model computing faecal waste generation using daily faecal sludge production in the population and latrine technologies with their waste emptying regimes and outputs of faecal waste contributions into the environment. Although not included in this paper, the tool also combines a quantitative microbial risk assessment to predict the probability of illness per flooding event.

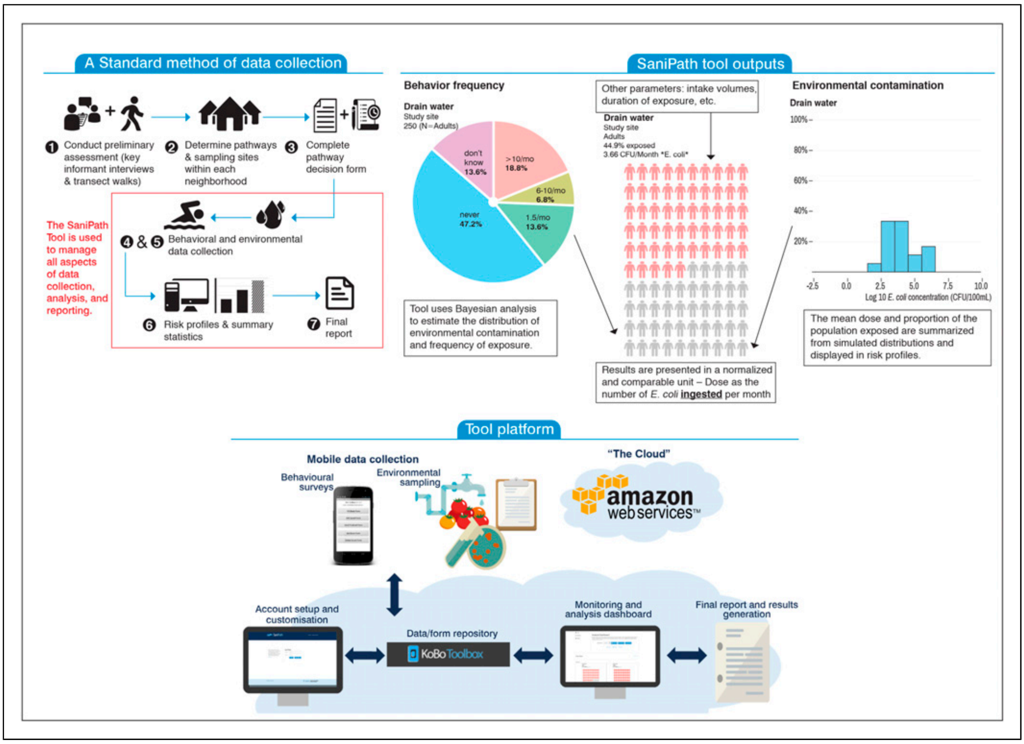

Figure 3. The integrated SaniPath data collection and risk-pathway assessments framework is comprised of (1) behavioural data collection involving preliminary assessments, interviews and transect walks; (2) collection and testing of environmental samples for *E. coli* levels at different selected community locations and (3) generation of risk profiles and summary statistics presented in a summary report. The outputs include ingested doses per month, mean doses and the proportions of exposed populations.

questions more comprehensively. Further descriptions are presented in Sections S1–S3. Supplementary Table S1 also shows the model or tool strengths and weaknesses.

Results

Outcomes from the assessments of the three tools

Question 1: Areas of the city with high health hazards

PFMT: Outputs for high emission parishes and contributing sources. The PFMT simulated the annual environmental rotavirus emissions reaching surface water (Figure 4) for all parishes in Kampala for the year 2016. Overall, 61 out of 96 parishes contributed greater than 1×10^{12} rotavirus particles per year. Some of these parishes with high emissions included Kasubi, Kibuli, Mutundwe, Mutungo, Kawempe, Banda, Bukasa, Lubya, Bwaise and Kyebando. Kasubi and Industrial Area are the parishes where the Lubigi Wastewater Treatment Plant (stabilisation ponds) and the Bugolobi Sewage Works (activated sludge and trickling filter system) are located, respectively. These two parishes were assigned all post-treatment emissions from centralised sewers and onsite technology

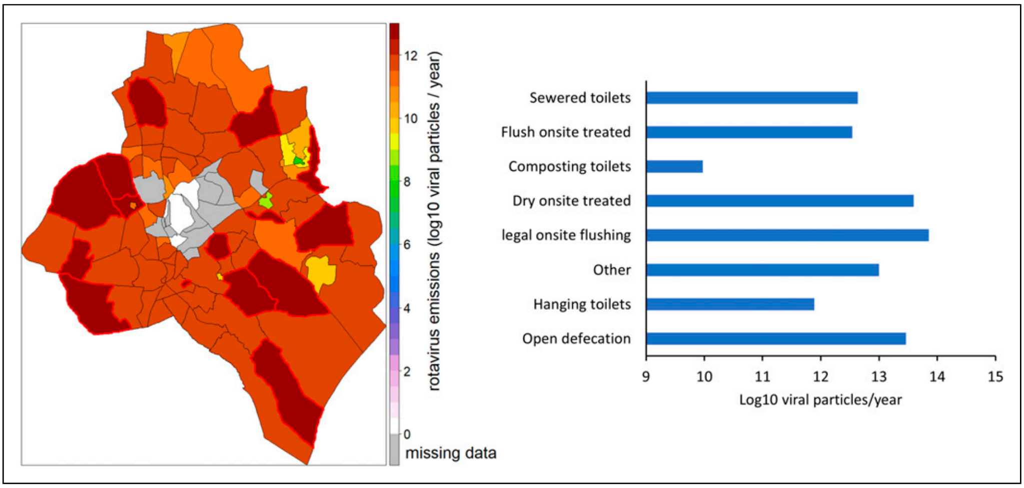

Figure 4. Simulated environmental annual rotavirus emissions from the parishes of Kampala and their respective contributing sources, with high emission parishes highlighted.

populations safely emptying their faecal sludge. Overall, parishes that had the highest relative health hazard due to elevated rotavirus emissions appear with darker shades of red as shown in Figure 4.

The most important contributing sources were illegal flushing (to open drains and to unknown) from water-based pit latrines and septic tanks with 13.86 log10 rotavirus particles/year, post-treatment of faecal sludge from non–water-based pit latrines with 13.60 log10 rotavirus particles/year, and open defecation with 13.46 log10 rotavirus particles/year. Sewer systems and water-based onsite toilets with faecal sludge emptying each contributed 12.64 and 12.54 log10 rotavirus particles/year into the environment. The combined treatment from the Lubigi and Bugolobi treatment systems achieved close to 1.0 log10 rotavirus particle removal.

HyCRISTAL: Influence of flooding on faecal contributions from latrines in Kampala. Currently, heavy rainfall events lead to considerable flooding in low-lying areas of Kampala. These are also areas characterised by dense, low-income housing and low-quality sanitation services. Flood models were overlaid on data identifying city-boundary-clustered sanitation facilities across Kampala (Figure 5), highlighting areas with high, medium and low concentrations of flooded latrines. Areas with a high density of flooded latrines were identified all across the city, but particularly within major hydrological catchment basins to the north-west and south-east. An elevation profile for the city is presented in Supplementary Figure S1. These latrines were assumed to contribute faecal matter into the flood water through three mechanisms: directly discharging into local open drains, floodwater washing out pit latrines and septic tanks, and informal latrine emptying and dumping into the local environment. Floodwater contamination models were run across a suite of plausible weather scenarios, and all showed a common pattern: a high 'first flush' of faecal contamination in the first hour of a flood event, followed by a lower, more continuous contribution. More extreme rainfall events led to the more rapid onset of contamination (6).

Dividing the faecal waste amounts in each sub-catchment by the relevant flood water volumes resulted in the faecal waste concentrations in the flood water (Figure 6). Under all scenarios modelled, the period under which concentrations were high was short. The peak faecal waste concentration occurred in the first hour of the storm event for all the scenarios we modelled.

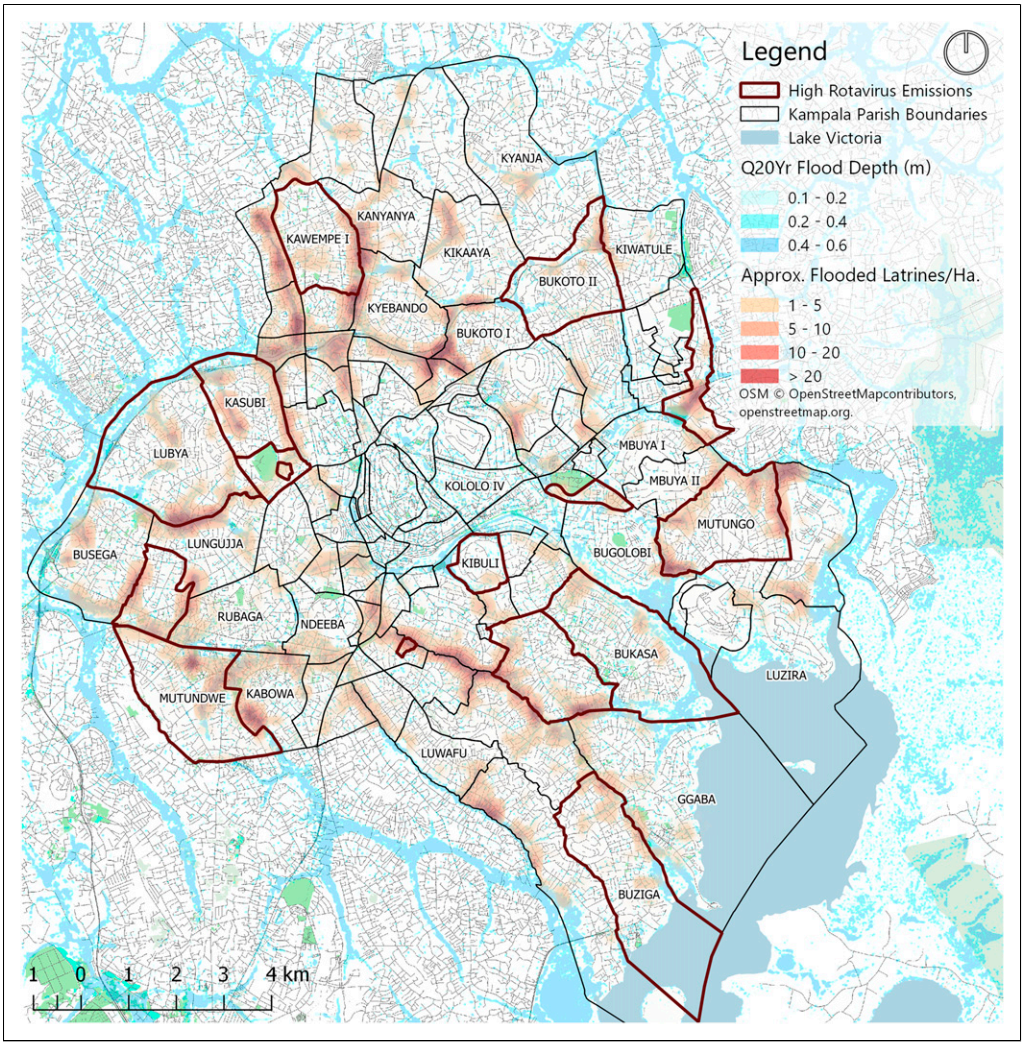

Figure 5. Concentration of flooded latrines across Kampala. High rotavirus emission parishes (highlighted dark brown lines) show an overlap between the pathogen flow and mapping tool and HyCRISTAL outcomes.

SaniPath: Identification of dominant faecal exposure pathways around Kampala. Nine faecal exposure pathways (spring water, floodwater, municipal drinking water, surface water, open drain, public latrines, soil raw produce and street food) were assessed in five low-income parishes, including Kabowa in Rubaga Division; Bwaise II in Kawempe Division; Kamwokya II in Central Division; Mbuya II in Nakawa Division; and Bukasa in Makindye Division. These pathways were primarily determined by the standard SaniPath tool protocol and local context as described in Section S3, Supplementary Tables S4 and S5. Supplementary Table S6 shows *E. coli* concentrations by pathway (type of environmental sample) and parish. High levels of faecal contamination were detected in the open drain water (mean *E. coli* concentration ranged from 6.32–7.72 $\log_{10}$ CFU/100 mL) and floodwater (mean *E. coli* concentration ranged from 5.53–6.49 $\log_{10}$ CFU/100 mL) in

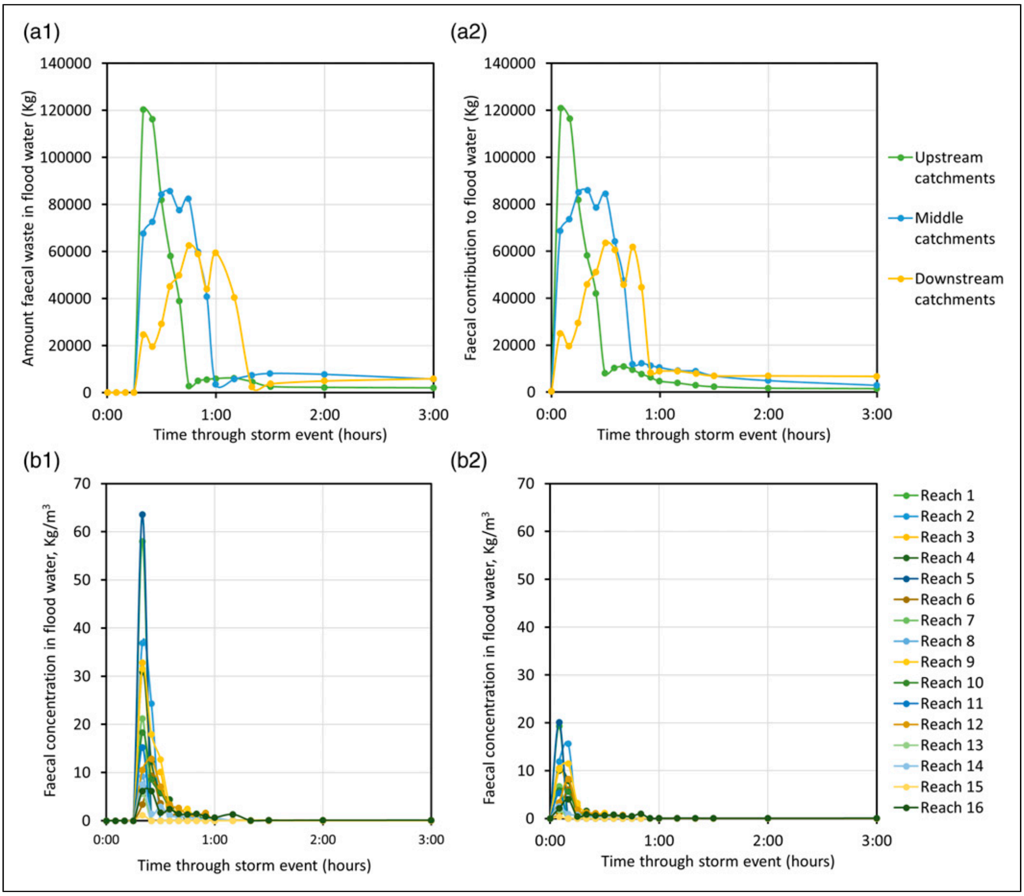

Figure 6. Cumulative contribution of faecal waste to floodwater; (a1) 1 in 5-year rain event on the dry ground under current climate conditions, (a2) 1 in 20-year rain event on the already-saturated ground in a future climate scenario, (b1) concentrations of faecal waste in floodwater in a 1 in 5-year rain event on dry ground under current climate conditions and (b2) 1 in 20-year rain event on the already-saturated ground in a future climate scenario. Reaches are the stretches of water bodies included in the study.

all five slum parishes. Surface water samples were only collected in Bukasa parish (mean *E. coli* concentration 4.31 $\log_{10}$ CFU/100 mL) and Bwaise Parish II (mean *E. coli* concentration 3.57 $\log_{10}$ CFU/100 mL). The raw produce and street food were highly contaminated (mean *E. coli* concentration >4.3 $\log_{10}$ CFU/serving) in Bukasa parish and Kamokya II Parish. The mean *E. coli* concentrations in municipal water from public standposts were low (<0.38 $\log_{10}$ CFU/100 mL) for all five parishes.

The adults and children in the majority of slum parishes were commonly exposed to open drain water and flood water (>50% of the population with at least one time of contact per month). More than 60% and 85% of adults and children in the study parishes reported consuming uncooked produce and street food, respectively, at least once per week. Contact with surface water was rare except for people who lived in Bukasa II parish (around 45% of the population reported at least one contact per month).

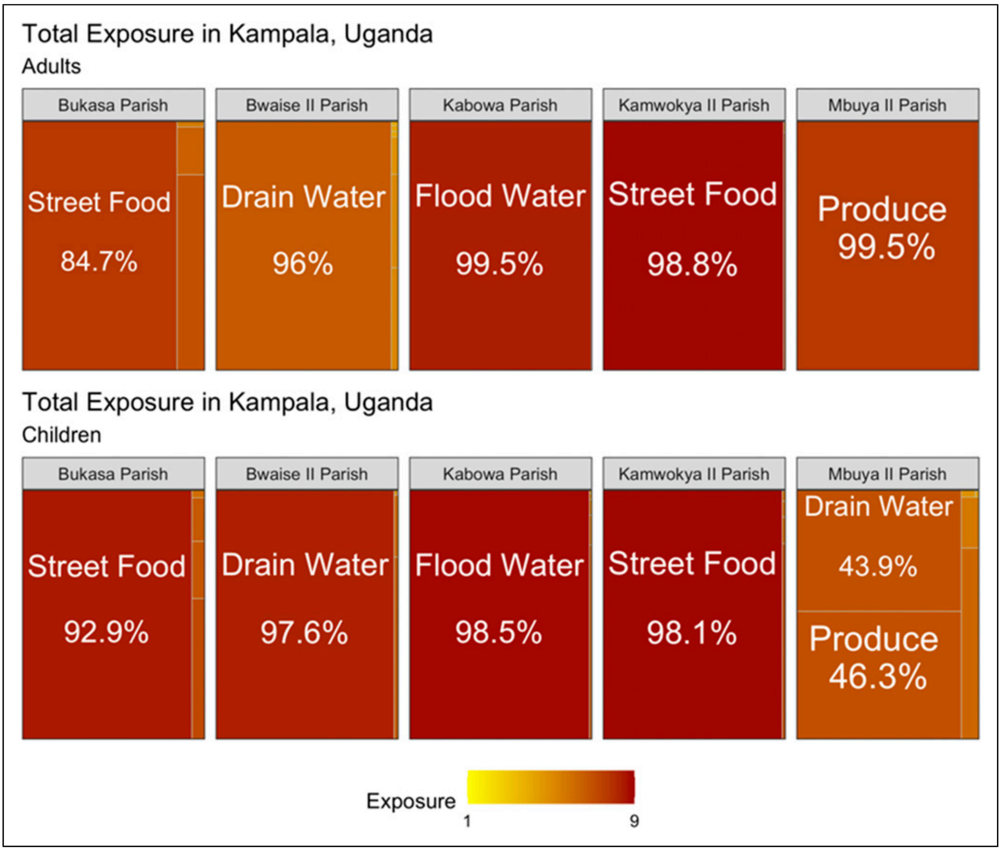

Figure 7. Dominant faecal exposure pathways for adults and children in selected parishes in Kampala. The size of each box indicates the contribution of a specific pathway to the total faecal exposure. The colour of the box indicates the magnitude of exposure as measured by *E. coli* $\log_{10}$ CFU ingested per month.

Overall, the dominant faecal exposure pathways (defined as those that make the greatest contribution to the total exposure) for adults and children in the study parishes of Kampala were open drains, floodwater, produce and street food. For children, open drains, floodwater and street food were the dominant faecal exposure pathways (Figure 7). The dominant pathways varied by parish. For adults, the average monthly exposure to *E. coli* ranged from 6.69 $\log_{10}$ CFU from open drains in Bwaise parish to 9.47 $\log_{10}$ CFU from street food in Kamwokya II parish. For children, the average monthly exposure to *E. coli* ranged from 6.72 $\log_{10}$ CFU from open drains in Mbuya II parish to 8.94 $\log_{10}$ CFU from street food in Kamwokya II parish.

Question 2: Household, community and city-wide interventions identified by the tools

PFMT: Incremental scenarios for sanitation improvement. We evaluated three scenarios for incremental sanitation improvements to reduce rotavirus emissions into the surface water. These were: 1) eradicating open defecation; 2) providing basic sanitation for 100% of the population (which includes ending open defecation, but also making all pit latrines lined so they can more easily be safely emptied and installing watertight septic tanks with leach fields for all non-sewer flush toilets); and 3) same as scenario 2 but also with safely managed sanitation for 100% of the population (i.e. all faecal sludge from onsite sanitation technologies is emptied and transported to centralised treatment

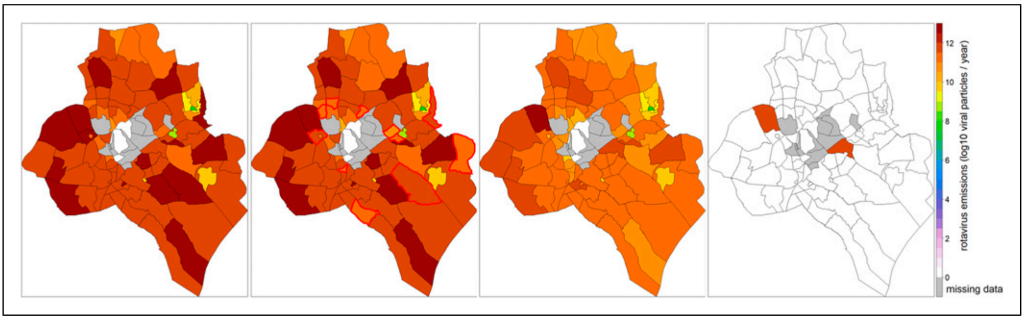

Figure 8. A comparison between baseline (left) and scenario outputs. Scenario 1 shows some highlighted parishes that benefited from the eradication of open defecation, scenario 2 shows the various parishes benefiting from the eradication of open defecation and elimination of illegal disposal of faecal sludge from onsite sanitation technologies, and scenario 3 shows all parishes benefiting from the eradication of open defecation and provision of safely managed sanitation for 100% of the population.

facilities by approved service providers). Figure 8 shows plots of the predicted rotavirus emissions for the baseline case and under each scenario. See Supplementary Table S3 for more information on scenario input data breakdown.

As indicated in Supplementary Table S3, for scenario 1, all open defecation was converted to lined pit latrines. The parishes benefiting the most from the eradication of open defecation included: Nakawa, Naguru I, Bukasa, Banda, Nakuylabye, Kamwokya II, Wandegeya and Mulago III with an average reduction of 0.42 log10 viral particles per year each compared to the baseline (Figure 8, scenario 1 – highlighted). An overall contribution of 17.8% reduction was achieved across all parishes. The reduction is limited because the fraction of the population practising open defecation is limited.

Almost all parishes benefited from the combined eradication of open defecation and eliminating the flushing of human excreta into the environment (Figure 8, scenario 2). Standing out, Kisenyi II, Kisenyi I, Buziga, Ntinda, Kagugube, Kisenyi III and Kiswa each saw reductions of about 1.14 $\log_{10}$ rotavirus particles per year on average. There was an estimated 69.6% reduction of rotavirus emissions per year across the city when compared to the baseline. The slightly increased volume of faecal sludge from onsite systems transported to treatment produced a 2% increase in rotavirus emissions (assuming that pit emptying did not change from the baseline's 23.9%) (Supplementary Table S3).

All parishes benefited from the improvements described in scenario 3 (open defecation is eradicated, unlined pits become lined and watertight, and all wastewater and faecal sludge is safely collected and conveyed to treatment (Figure 8, scenario 3)). The two parishes of Kasubi and Industrial Area (dark orange in the figure), where the treatment plants are located, received all post-treatment rotavirus emissions reaching the surface water. Compared to the baseline, these two would experience a 107% increase in post-treatment onsite sanitation emissions. However, an overall reduction in emissions of about 97.1% was achieved across all sanitation systems when 100% of the population receives safely managed sanitation facilities in this scenario. No treatment removal improvements were implemented in any of the scenarios.

Assuming that there are no leakages from sewer systems or faecal sludge emptying and disposal activities in scenario 3 may be unrealistic. Furthermore, the sewage and faecal sludge treatment facilities currently available may not have sufficient capacity to treat waste from all onsite systems across the city. Upgrades to the faecal sludge emptying fleet and increasing capacities at centralised wastewater treatment facilities would be necessary for this scenario to be more realistic.

HyCRISTAL health hazard model: reducing faecal waste entering floodwater and the subsequent health impacts. The model explored the impact of formal versus informal emptying practices, emptying latrines ahead of a storm event and the removal of direct connections between pit latrines and drainage systems. To drastically reduce the initial 'plug' of waste entering the floodwater, direct connections should be removed, alongside formal emptying of any recent waste (in lieu of informal dumping practices). To minimise the subsequent faecal contributions to the floodwater, pit latrines should be (formally) emptied ahead of the flood event, and be floodproofed where practicable (Figure 9).

This combination of good management practices (the measures in Figure 9(b) and (c), excluding flood proofing, which would be a construction intervention) reduced the affected population by an average of 70% under current climate conditions across the range of modelled pathogens, and by ~30% in the most extreme future climate scenario.

SaniPath: exposure assessment and potential intervention benefits. The environmental contamination and contact behaviour data revealed a mixture of dominant pathways of exposure to faecal contamination in the selected parishes, with varying exposure risks for adults and children. Because the data were used to identify the pathways that posed the greatest exposure risks in each study parish and to estimate faecal exposure by pathway, optimised intervention recommendations can be made to mitigate these risks. Assessing the potential health impacts of specific interventions in respective parishes was out of study scope.

However, the results of the SaniPath assessment lead to the following recommendations: (1) reduce exposure to contaminated open-drain water and flood water by improved sanitation and drainage infrastructure; (2) promote handwashing at household level; (3) promote safe handling of

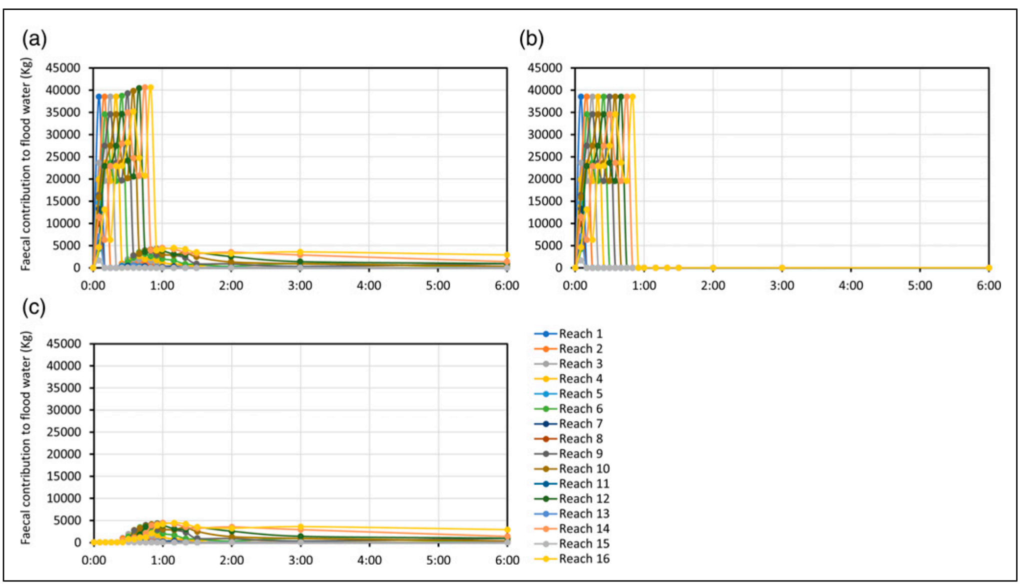

Figure 9. Impact of faecal waste management interventions on faecal waste concentrations in flood water through the modelled catchment: (a) baseline, (b) removing informal storm drain connections and implementing formal emptying practices, (c) emptying latrines ahead of storm events and floodproofing where practicable.

food from the farm-to-fork to prevent the introduction of faecal contamination into uncooked produce and street foods; and (4) sensitise the public about health risks and exposure reduction from the dominant pathways identified in the study parishes.

Integration of tools' interventions

Collectively, the three tools allowed for the combination of results targeting the most vulnerable parishes of the city and thus provided a more comprehensive assessment of the sanitation and public health conditions in Kampala than when a single tool was applied. Moreover, these results were integrated into recommendations for sanitation technology, infrastructure, hygiene and behaviour management interventions applicable at household, community and city-scale levels. The interventions illustrate potential incremental sanitation, infrastructure and hygiene improvements that could help to limit exposure to faecal contamination and enteric pathogens in the environment.

A combined assessment of the baseline conditions. In line with KCCA's Question 1, the PFMT and the HyCRISTAL tools highlight areas of the city with higher relative health hazards using representative disease incidence and faecal contribution input data, respectively. Both tools estimated key contributing sources, such as open defecation and illegal disposal of wastewater and faecal sludge. The PFMT adds contributions from the treated (safely managed) proportions, highlighting the relevance of wastewater treatment. HyCRISTAL integrates the influences of near-term future climate scenarios on faecal concentrations in the environment facilitating short and long-term decision making. Parishes predicted to have high rotavirus emissions by the PFMT coincided with areas of high faecal contributions identified by the HyCRISTAL tool, including Bukasa, Kasubi, Kibuli, Mutundwe, Mutungo and Banda, among others (Figures 1 and 2). The SaniPath tool confirmed that the risk of exposure to faecal contamination was high in such areas, for instance, in Kasubi, and that floodwater is a dominant exposure pathway.

Recommended interventions based on integrated tool results

At household level. At household level, the PFMT suggests providing lined pit latrines with proper emptying and treatment practices across parishes with the most open defecation, such as Banda, Bukasa, Nakulabye, Nakawa and Mulago III; lining and slabbing unlined and non-slabbed pit latrines, making septic systems watertight with leach fields, and regularly emptying onsite facilities to reduce significant loading of rotavirus emissions into surface water. In addition, the HyCRISTAL tool recommends that direct latrine-to-drain connections and informal local dumping should be eliminated to limit environmental faecal contamination. Moreover, the tool recommends that emptying of pit latrines and septic tanks before flood or storm events significantly reduces the health hazard in the environment.

The SaniPath tool also identified open drains as an important pathway of exposure to faecal contamination at a household level. Therefore, the interventions identified by the PFMT and HyCRISTAL tools to reduce this exposure would likely lead to a reduction in enteric infections. Once pathogens reach the environment, exposure depends on individual behaviour. The various dominant faecal exposure pathways identified across the study parishes, particularly open-drain water and flood water pathways, are in concordance with the PFMT and the HyCRISTAL outcomes, indicating that faecal material is often indiscriminately discharged into the environment from onsite facilities.

The findings of the SaniPath assessment indicated that children had higher total faecal exposure compared to adults. Children were largely exposed through contact with contaminated drain water and floodwater and consuming contaminated raw produce and street food. Thus, at the household scale, the SaniPath assessment recommends hand washing, safe storage and handling of food, and the washing and peeling of raw produce before consumption across the high-risk parishes. On the other hand, both the PFMT and HyCrystal findings justify the relevance of improving household sanitation facilities, particularly in high-risk parishes. For such areas, the tools recommend formal emptying of faecal sludge, but more so ahead of storm events.

At community and city-scale levels. The sanitation type, design, faecal sludge disposal practice and household hygiene within the community are associated with faecal pathogen contamination of the environment and the potential for human exposure. Communities with poor to limited sanitation services may have a highly contaminated environment. Therefore, the SaniPath tool recommends mass community sensitisation to help raise awareness on how everyday behaviour can lead to potential exposure to faecal contamination in water, food, and the environment, and to inform community residents how they can reduce their risks associated with the different exposure pathways.

Flooding can be a local phenomenon in low-lying areas. For such areas, the results from the HyCRISTAL tool advocate for the construction of public facilities that prevent the introduction of faecal material into the surroundings and stormwater drains.

City-wide recommendations can be guided by the results from the three tools. The PFMT showed that ending open defecation alone or only providing basic sanitation coverage is insufficient. They should be integrated with the proper emptying and disposal of faecal sludge from onsite sanitation facilities, and the consequent treatment of collected wastewater from all parishes. The results of the SaniPath assessments in Bwaise II and Kasubi parishes may be extended to other parishes with high open defecation, illegal sewer connections and faecal sludge flushing into open drains. The HyCRISTAL and the PFMT findings strongly support a recommendation for the formalisation and monitoring of faecal sludge management activities, sewer connections, and wastewater treatment, which will limit the introduction of faecal sludge into open drains and waterways. For the contamination that eventually enters the open drains, limiting all exposures, as suggested by the HyCRISTAL and SaniPath tool results, will require improving dilapidated drainage channels in flood-prone areas, and designing appropriate and inaccessible stormwater drainage. When household-level interventions for improving onsite sanitation and safely managing faecal sludge are applied among the urban communities, they can result in reduced hazards, exposure and associated risks across the city.

Discussion

Assessment outcomes from the integration of the three tools have demonstrated augmented support towards improving WASH under changing climate conditions for Kampala. Whilst the PFMT explores baseline pathogen emissions and changes to those emissions due to sanitation interventions, the HyCRISTAL tool adds the influences of climate change and infrastructure management on human excreta in the environment. Moreover, the SaniPath tool complements the other two tools by identifying high-risk exposure pathways to target with behavioural interventions in addition to infrastructure changes.

The application of the three tools in the same city simultaneously provides strong evidence derived from alternative scientific approaches and scenarios to facilitate decision making by urban authorities and utilities concerning prioritising investments and interventions, the efficient allocation of meagre resources and the deployment of constrained capacity. Therefore, the recommended interventions are the result of a richer assessment addressing the respective WASH challenges to improve health outcomes, than when an individual tool is applied.

However, some key gaps for the improvement of these tool outcomes remain. For instance, the PFMT's emissions outputs are only for rotavirus. The absolute values from the tool may therefore not fully capture total pathogen loading, as bacteria, protozoan parasites and helminths have not been included. There is also some uncertainty in the faecal sludge management and sewer leakage assumptions in the HyCRISTAL and the PFMT tools. Such activities are informal, undocumented and unregulated (Schoebitz et al., 2016; Strande et al., 2018).The relevance of both tools is, however, in estimating relative changes in contamination associated with specific interventions. The models applied in both the HyCRISTAL and PFMT have not been validated in the specific Kampala context, and their validation is out of the scope of this study. Nevertheless, the tools focus on the relative differences when examining the potential impacts of interventions and highlighting areas of high risk. The model underlying the PFMT has been evaluated in a lot of detail previously and performed reasonably well at the global scale (Vermeulen et al., 2019). The SaniPath tool studied exposures to faecal contamination only in a few parishes. Although the results of these assessments could be extrapolated to other similar neighbourhoods across Kampala, population demographics, exposure behaviours and susceptibility to infection and disease can be diverse and, therefore, health risks may vary by parish.

For the tools to be most useful, co-development of possible WASH improvement scenarios needs to be done in partnership with local WASH practitioners and urban planners. WASH decision support tools need to address and transcend their limitations. Palaniappan et al. (2008) compiled key gaps in WASH support resources, which limit the evaluation of potential solutions. Such gaps include costs, financing, scalability, social acceptability, ease of use and replicability, among others. Thus, building comprehensive tools that can address WASH-related questions for the different users and platforms can be challenging, and is clearly out of the scope of this study.

One of the approaches towards evaluating alternatives is to assess how health impacts are achieved from WASH interventions (Robb et al., 2017). The WHO developed SSP guidelines for practitioners to develop risk-based interventions when using wastewater and disposing excreta so as to protect public health (WHO, 2016; Winkler et al., 2017). The stepwise guidelines aimed at steering users to identify sanitation chain-wide health risks and prioritise beneficial interventions are implicitly demonstrated by the three tools. Collectively, the tools identify priority areas for improving sanitation and hygiene in Kampala. This includes identifying and quantifying potential hazards (rotavirus emissions, faecal and *E. coli* concentrations in respective compartments), and identifying interventions that bring the most reduction of the hazard when combined. However, both the PFMT and HyCrystal tools indirectly assume high exposure risk areas as those with relatively high hazard levels. Their management scenarios also do not ascribe health-risk controls in the sanitation management interventions or in the reuse of wastewater and excreta. The SaniPath tool, however, generated risk profiles for the different parishes and divisions in Kampala but only suggests actions for reducing exposure to the dominant hazard pathways.

Therefore, the current scope of the tools is not aimed at completing the SSP cycle, but to demonstrate the richness of the combined assessment and address the questions raised by KCCA. Application of the three complementary tools in our study is a step towards improving sanitation, reducing the risk of enteric diseases and enhancing the quality of life for communities.

To guide this study's assessments, KCCA developed two questions concerning the identification of key hazard sources and developing technological and behavioural interventions to reduce health risks from exposure to human excreta. The Kampala Sanitation Improvement and Financing Strategy (Salian et al., 2020) aims to steer planning and development towards improving access to WASH to achieve SDGs 6.2 and 6.3 by 2030. Therefore, even more questions concerning Kampala's WASH challenges presented in the introduction should be addressed by prospective support tools evaluating potential universal and equitable solutions. In an enabling institutional framework and legal requirements environment, outputs from three tools can be combined with other decision support resources, for instance on intervention costs, to address wider knowledge gaps.

Kampala was used only as an example in this study. The assessment framework described here was conducted through modelling, community assessments, and measuring microbial contamination in the environment. Consequently, this approach is readily replicable anywhere in the world.

Conclusions

The goal of this paper was to address questions raised by KCCA. Independent assessments from the tools identified the highest health hazard or impacts from human excreta and sewage and generated evidence-based recommendations to reduce health risks from exposure to the identified hazards. Below, we present the following conclusions and incrementally applicable recommendations for household-, community- and city-scale levels:

1. Areas or hotspots predicted to have the highest health hazard overlapped between the PFMT, HyCRISTAL and SaniPath assessments, therefore, identifying the prevalence of poor sanitation conditions, including open defecation contributed by a small population and informal disposal of faecal sludge into stormwater drains. Kabowa and Bwaise parishes were two overlapping hotspots with high health-risk profiles, characterised by contaminated floodwater and drain water as the dominant exposure pathways.
2. Despite the importance of other exposure pathways, the assessments revealed that informal disposal of human excreta into open stormwater drains is a key contributor to health hazards in the environment.
3. An intervention that combines the provision of lined pit latrines with proper emptying and treatment practices, preventing latrine to open drain connections, constructing watertight onsite sanitation technologies, and appropriate emptying and disposal of faecal sludge is crucial for reducing faecal contamination in the environment and the consequent health risks. The intervention should target the identified high-risk parishes in Kampala, including Kabowa, Bwaise, Kamwokya, Kasubi, Kibuli and Mutundwe.
4. Safe emptying, transport and disposal of faecal sludge from onsite sanitation technologies are more important when conducted before a rain or flood event. These interventions are feasible even when there is limited sanitation and poor drainage infrastructure, such as in flood-prone areas.

Overall, combining the assessments from the three tools produces a more comprehensive characterisation of sanitation-related hazards in the environment and allows more detailed guidance for the development of local incremental and far-reaching interventions. The outcomes from these tools can complement other WASH support resources that integrate aspects of sanitation implementation, such as cost, financing, replicability and scaling, among others. A summary of the outcomes and recommendations from the assessments is presented in Supplementary Table S7.

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Supplemental Material

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