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Implementation and monitoring of on-site sanitation systems to mitigate public health risks in low- and middle-income contexts

by Freya Mills

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Professor Juliet Willetts, Dr Tim Foster and Professor Barbara Evans

University of Technology Sydney
Institute for Sustainable Futures

June 2025

Certification of original authorship

I, Freya Mills, declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy through the Institute for Sustainable Futures at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Format of thesis and included publications

This thesis is a ‘thesis by compilation’ as described in the University of Technology Sydney’s Graduate Research Candidature Management, Thesis Preparation and Submission Procedures 2024 (section 9.1), comprising a combination of chapters and published/publishable works.

The included publications are:

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3. Mills, Freya, Siti Maysarah, Cindy Priadi, Juliet Willetts, Barbara Evans, and Tim Foster. “Evidence to inform onsite well and sanitation siting criteria: Risk factors associated with well contamination in urban Indonesia.” Submitted to IWA Journal of Water & Health 2nd February 2025 and under review.
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Statement of contribution of authors

This declaration concerns the following article that is submitted for PhD examination:

All were co-authored and the authors agreed that I was the main contributing author for all articles and agreed on their nature and extent of contribution. The nature of contribution is defined in the following categories: 1. Conceptualization including formulation of the scientific problem and planning of the field research and method design, 2. Data collection, 3. Review of literature, 4. Data analysis and interpretation of results, 5. Preparation of the manuscript, 6. Submission process including revisions 7. Critical review, feedback and inputs. The extent of contribution refers to the proportion of each aspect that an author contributed to.

Paper 1

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Declaration by co-authors

Co-author	Nature of contribution*	Extent of contribution#	Signature	Date
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Juliet Willetts	1. Conceptualization 3. Review of literature 5. Prepared manuscript 6. Submission 7. Critical review	25% 80% 10% 5% 60%	Production Note: Signature removed prior to publication.	17/01/25
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Paper 2

Mills, Freya, Tim Foster, Christine Moe, Nuhu Amin, Pengbo Liu, Mahbubur Rahman, Barbara Evans, and Juliet Willetts. "Unsafe containment: Public health risks of septic tanks discharging to drains in Dhaka Bangladesh." *PLOS Water* 3, no. 12 (2024): e0000325. https://doi.org/10.1371/journal.pwat.0000325

Paper 2 Declaration by co-authors

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Abbreviations and key terms

Recognising that definitions of different aspects of water and sanitation vary, below is a summary of the definitions used for key terms.

- Borehole – A drilled well, typically with casing and pump.
- Cesspool – Also called a wet pit latrine, receives inflows from flush toilet. Pit is not fully sealed to allow liquid to seep into surrounding soil.
- Containments – another term for OSS meaning the tank or pit infrastructure.
- Contained – step in the sanitation service chain that relates to the safe storage of excreta within an on-site system and, according to SDG definition, does not allow release of untreated excreta to the surface environment.
- Dry latrine – Also called pit latrine, it is a permeable pit, typically semi-lined, that does not receive water inflows, just excreta, cleansing materials and often solid waste.
- Dug well – large diameter, often shallow well, typically not drilled, can be covered or uncovered and use buckets or pumps for extraction.
- Effluent – Liquid discharge from septic tanks or pit latrines that typically refers to the piped discharge rather than liquids leaching into soil (leachate).
- FSM - Faecal sludge management
- HIC - High income country (i.e. as defined by World Bank)
- LMIC - Low- and middle-income countries
- OSS - On-site sanitation
- QMRA - Quantitative Microbial Risk Assessment
- Sanitation service chain – the sequence of steps for managing sanitation from generation to final disposal. It includes access or user interface, containment, emptying, transport, treatment, disposal and reuse.
- Septic tank system – Also commonly referred to as "septic tank", is typically a two-chamber watertight tank receiving blackwater and sometimes greywater inflows, that discharges to a subsurface infiltration system and requires regular emptying of settled sludge.
- SFD – Excreta (or Shit) Flow Diagram is a visual representation of how excreta in an area are managed across the service chain.
- Sludge – settled solids that accumulation in on-site sanitation systems.
- SDG - Sustainable Development Goal

Abstract

Sanitation has been recognised as one of the greatest public health achievements of the last century. Yet in many low-income countries, inadequate sanitation still contributes to thousands of diarrhoeal deaths annually. While more people globally use an on-site sanitation system (OSS) rather than a sewer, there is limited understanding of OSS implementation and performance across different contexts. Unsafe management of OSSs can lead to the release of untreated excreta into the environment, exposing people to pathogens, particularly through surface waters and water supplies.

This thesis examines health risks associated with OSSs in low- and middle-income countries (LMICs) from a public health engineering perspective. This research aims to enhance understanding of these risks through novel empirical studies on sanitation implementation and by identifying how monitoring data can better reflect health risks. The thesis by compilation includes four papers: a literature review on sanitation investment drivers, two empirical studies examining the relationship between OSS implementation and faecal contamination of drains and groundwater, and an investigation of indicators to better assess health risks beyond those monitored for the global sanitation target of safely managed sanitation.

This research revealed that many OSSs fail to meet design, siting, or management standards and pose significant public health risks. Three-quarters of systems classified as ‘safely managed sanitation’ by global monitoring still present health risks to the users, public or workers. Many septic tanks discharge directly to drains and release numerous pathogens in high concentrations with little improvement over direct toilet discharge. The prevalence of hazards varied between and within countries and monitoring of key features of OSS implementation and the surrounding environmental context is necessary to identify and prioritise risks. Empirical data, including on pathogens, can improve understanding of how implementation influences risks and which failures or contamination pathways to prioritise. Improved implementation or alternative solutions are needed, particularly for effluent management and OSS in impermeable soils or shallow groundwater areas. Future research could replicate these methods at larger scales or different areas to validate findings across different contexts, address remaining gaps related to pathogen removal in OSS, and support translating these findings to practice.

This thesis contributes new evidence on pathogens and health risks associated with OSSs and presents improved methods for monitoring these risks at various scales. This research can improve awareness of the multiple risks associated with OSSs and emphasises the importance of using local data to prioritise public health in sanitation investment decisions.

PART I

1. Introduction

- Background and objectives
- Research approach
- Thesis outline

1.1 Background and objectives

1.1.1 Research context

Sanitation plays an important role in safeguarding public health, protecting the environment and supporting economic development. However, only half the global population has access to safely managed sanitation services (UNICEF and WHO, 2023). Progress needs to increase fivefold to achieve universal access by 2030, as is targeted in the Sustainable Development Goals (SDG). Safely managed sanitation services, as defined for SDG reporting, require access to an improved toilet that is not shared and that excreta are managed from the toilet to ultimate treatment and disposal. In the least developed countries, only 27% of the population have access to safely managed services, meaning that most excreta are disposed untreated to the environment (UNICEF and WHO, 2023). Consequently, faecal-related diseases such as diarrhoea, cholera, typhoid and helminth infections remain prevalent in many low-income countries (Goddard et al., 2020; UNICEF and WHO, 2023). In 2019, 1.4 million deaths were attributed to unsafe water, sanitation and hygiene, while diarrhoeal diseases remain a leading cause of death among children under five (Wolf et al., 2023).

More people globally use on-site sanitation systems (i.e. septic tanks and pit latrines) than sewer connections. Between 2000 and 2022, the rate of increase in access to an on-site sanitation system (OSS) was twice the increase in connection to sewers (UNICEF and WHO, 2023). In LMICs, OSSs are the primary type of sanitation in both urban and rural areas and include a diverse range of systems: septic tanks, water-flush and dry pit latrines, and other improved pits and tanks. For SDG monitoring, the criterion for 'safely managed' requires that excreta from OSSs are either contained and stored in-situ or contained, emptied and treated off-site. Ensuring safely managed OSS services is often more complex than sewerage (off-site sanitation) due to the need to manage both solid (sludge) and liquid (effluent) streams, multiple actors involved across the service chain and often fragmented responsibilities and regulations (Strande et al., 2023). The proportion of OSSs that are considered safely managed (24%) is much lower than for sewer systems (33%), which is partly due to the challenges of ensuring safe management across all steps but also due to a lack of data related to OSSs (UNICEF and WHO, 2023).

Historically, protecting public health has driven sanitation investments, and the sanitary revolution is often considered one of the most important public health achievements of the 20th century (Mara et al., 2010). As diarrhoeal diseases became less common in high-income countries (HICs), sanitation investments shifted focus towards environmental protection, private sector engagement, cost and resource recovery (Brugger, 2021). However, many LMICs face ongoing issues with faecal-related diseases and insufficient progress in providing universal access to sanitation services. Therefore, it remains crucial that sanitation investments in LMICs continue to prioritise public health objectives that reduce human exposure to pathogens. Yet research indicates that in many LMICs, there has been insufficient consideration of the health risks associated with OSS, particularly in dense urban areas, and little government coordination of sanitation interventions to achieve health outcomes (Cummings et al., 2016; Foster, Falletta, et al., 2021; Satterthwaite et al., 2015).

The research on health risks related to sanitation has centred on measuring faecal pathogens in the environment, human behaviours resulting in exposure, and the health impacts from exposure (Goddard et al., 2020). These approaches come from a public health perspective and pay less attention to the sources of contamination and what specific aspects of sanitation infrastructure, implementation, or management need to be addressed to reduce pathogens in the environment. Environmental monitoring has revealed high concentrations of faecal contamination and frequent exposure through various transmission pathways but often failed to indicate how sanitation systems and their failures contribute to this (Goddard et al., 2020; Y. Wang et al., 2022). Recent rigorously conducted intervention trials found little or no improvement in diarrhoea in young children from basic sanitation improvements (Contreras & Eisenberg, 2019; Cumming et al., 2019; Sclar et al., 2016). These studies assessed access to improved toilets without considering the safe management of excreta or whether full coverage was achieved, meaning that the intervention was unlikely to have addressed the multiple possible pathways that sanitation can contribute to faecal transmission (Cumming et al., 2019).

The impacts of inadequate sanitation services on health are expected to become increasingly significant with urbanisation and climate change. The use of OSSs increased at seven times the rate of sewer connections in urban areas over the last 20 years, and this is likely to further increase with rapid urbanisation in many cities in LMICs (UNICEF and WHO, 2023). OSSs are increasingly being promoted as an important component of city sanitation plans, with the Citywide Inclusive Sanitation (CWIS) approach emphasising that universal sanitation cannot be achieved with centralised sewerage alone (Gambrill et al., 2020; Schrecongost et al., 2020). In rural areas, 800 million people still do not use improved toilets (UNICEF and WHO, 2023), and efforts to reduce open defecation will likely cause the construction of on-site sanitation systems. There are also many potential impacts of climate change on sanitation systems, including the increased risk of damage or overflow of on-site systems and frequent increased exposure to contamination from frequent flooding (WHO, 2019). If the investments in sanitation to achieve the SDGs are to achieve the health benefits expected and required, greater attention and evidence are needed on how different sanitation solutions address health risks.

1.1.2 Rationale for research

Although it may appear counter-intuitive, governments, engineers and development partners often make sanitation investment decisions with limited consideration of how different options will impact public health. Sanitation plays a vital role in reducing pathogens in the environment, but there is often insufficient data or awareness regarding how these risks relate to specific sanitation systems in different contexts. This is a particular issue for OSSs, which are most prevalent in the areas most at risk from faecal-related diseases, yet OSSs often receive little attention due to the perception they are a temporary solution until centralised sewer systems are built (Strande et al., 2023). With little oversight and often weak regulations, OSSs are being implemented, used and operated in ways that may not benefit public health and may even increase risks in certain contexts. This is a critical issue given the rate of increase of OSSs in urban areas, where standards related to well separation distances and population density limits are often unmet. There are many potential issues in how OSSs are designed, installed, used or managed that lead to the release of inadequately treated excreta to the environment (Peal et al., 2020). Failing to consider the hazards associated with OSS failures may cause human exposure to pathogens and investments that do not effectively reduce health risks.

OSSs are often assumed to be simple and well-understood technologies. However, there is a general paucity of research related to health risks, especially considering the diversity of types and contexts in which OSSs are used. Recent reviews on pathogens and sanitation systems predominately included research from HICs, laboratory studies, and dry pit latrines, leaving gaps in data relevant to wet OSSs (i.e. septic tanks and cesspools), their use in-situ, and from LMICs (Adegoke & Stenstrom, 2019b; Musaazi et al., 2023; K. Orner et al., 2019; M. Wang et al., 2021).

Global monitoring of sanitation has shifted from only assessing toilet access to now monitoring containment, emptying and disposal (WHO & UNICEF, 2018). Measuring toilet access, rather than whether excreta are safely managed, is one explanation for why recent health impact studies found limited benefits from sanitation interventions (Mertens et al., 2023). Environmental monitoring is improving rapidly with new methods and technologies and can monitor a range of pathogens. However, these studies often focus on human interactions and exposure rather than identifying the sources of contamination or the technical or service improvements that can reduce risks.

To increase awareness of potential health risks associated with OSSs and make informed improvements, we need more evidence on how OSSs are implemented and used in LMICs and the risks these may present. The gaps related to water-based sanitation are a particular priority given the common and increasing use of flush toilets and the added challenge of managing both liquid and solid waste streams from septic tanks and cesspools. Improvements in monitoring health risks are also essential to quantify the variety of risks associated with OSSs across the service chain in different contexts. This information can help identify and prioritise risks and plan mitigation efforts to improve the effectiveness of sanitation investments to progressively reduce public health risks in LMICs.

1.1.3 Research aims and questions

The aim of this research is to improve understanding of the extent of faecal-related health risks associated with on-site sanitation as they are implemented in LMICs. This research aims to develop new evidence on the health hazards related to on-site sanitation as they are used in-situ in LMICs and explore how different approaches to monitoring OSSs can improve the assessment of health risks from a public health engineering perspective.

The main research question and two sub-questions are:

To what extent are on-site sanitation systems implemented and monitored in ways that reduce public health risks in low- and middle-income contexts?

- ***RQ1: To what extent are on-site sanitation systems implemented in ways that reduce public health risks?***
- ***RQ2: How can monitoring data better reflect health risks?***

Table 1.1 provides definitions of the key terms used in these research questions, which touch on the boundaries of the research further outlined in Section 1.2.3.

Table 1.1 *Definition of key terms used in research questions*

Extent	Refers to the need for quantifiable evidence on the nature and significance of the risk to inform decisions between systems, operation and implementation.
Implemented	Implementation includes infrastructure design, siting, construction, use, operation and management, recognising that many systems are not implemented as intended (i.e. sanitation failures). The implementation also considers the physical context in which they exist, noting that soil type, groundwater depth, population density, rainfall, water use, and exposure can all influence hazards and risks.
Monitored	Relates to the range of methods used to assess on-site sanitation to understand how they are implemented and the risks they pose.
Monitoring data	Focuses on the different monitoring methods and types of data produced, not the topic of monitoring more broadly (i.e. it does not consider the enabling environment for monitoring and data use).
Reduce public health risks	Public health risks related to exposure to pathogens from human excreta, recognising there are also diverse vector-borne diseases and social risks related to inadequate sanitation. An engineering approach is taken to assessing and reducing risk, focusing on improving system safety and functionality to reduce the likelihood and consequence of a hazard or failure event with only limited consideration of behavioural aspects of exposure or the health aspects related to risk of infection.
Reflect risks	Data that demonstrates or quantifies hazards or potential risks to provide evidence to input to decision processes but not methods to assess risks.
Context of LMICs	Recognising that sanitation systems, implementation and hazards differ between low- and high-income contexts. The priority of this research is on areas in LMICs with case evidence from Asia and Africa.

1.2 Research approach

1.2.1 Research perspective

My engineering background and field experience informed the approach to this research, which is driven by the perspective that evidence is important to improve understanding and inform decisions. The research approach includes the identification of gaps in evidence, collection of new evidence from OSSs in LMICs and assessing monitoring approaches. My field experience demonstrated that sanitation systems are often not implemented as intended in designs or standards and that understanding risks requires assessing how sanitation systems are implemented and function in-situ (not in a laboratory or spreadsheet). This is important for OSSs, which are often self-built with limited guidance or regulation.

The other driver for this research is the need for local data to inform decisions. This is because OSSs include a breadth of technologies that perform differently and pose different risks depending on the environmental and physical contexts in which they are used. While OSS is a collective term, it refers to diverse technologies, and systems are often adapted to their physical setting or local understanding of design. Many sanitation masterplans or sanitation improvement programs are not based on evidence of the type or implementation of sanitation systems in that context. The modifications of OSS design or implementation by government or development partners I observed in the field demonstrated a poor understanding of the principles and function of OSSs and the risks associated with solid and liquid streams.

My approach to this thesis was to create a useful set of complementary studies showing different angles of this topic, which includes a literature review, in-depth empirical studies and analysis of large global datasets. The objective was to collect in-situ data to reflect the actual conditions of systems being used in low-income urban areas. Although the studies were predominately conducted in Asia, there were varied environmental and physical characteristics that can also be found in other LMICs globally.

As per my professional research career, the studies were all conducted in partnership with local research partners and development agencies. This enables a more in-depth understanding of the local context and how the research is relevant to practice and policy. The areas of the in-depth studies are also locations where I have previous in-field experience and understanding of the broader physical, political and social factors influencing sanitation. The research Papers 2, 3 and 4 were funded by development partners WSUP, DFAT and SNV respectively, although only SNV was involved in the analysis as co-authors on Paper 4. As detailed in the statement of contribution tables, I was responsible for research conceptualisation, funding, design of methods and tools, support in data collection, data cleaning, analysis and writing the papers. While I am the lead author, all papers have multiple co-authors, and I value the opportunity to acknowledge the contributions of different researcher roles to the academic research outputs.

1.2.2 Research design and methods

This section summarises the scope of this research and outlines the mixed methods approach to addressing the research question. From the literature review, there was a gap in research on the health risks related to OSSs as they are implemented in practice, particularly relating to the hazards associated with poor containment of liquid flows from septic tanks and cesspools. The F-diagram illustrates faecal-oral disease transmission routes, showing how pathogens spread from faeces via fluids, fields, flies, fingers and food to human hosts, with sanitation, handwashing and water treatment acting as barriers to transmission (Ntajal et al., 2020; Wagner et al., 1958). WHO's Guidelines on Sanitation and Health (2018) updated this figure (see Figure 3.1), emphasising that sanitation can be both a barrier and a hazard when unsafely managed.

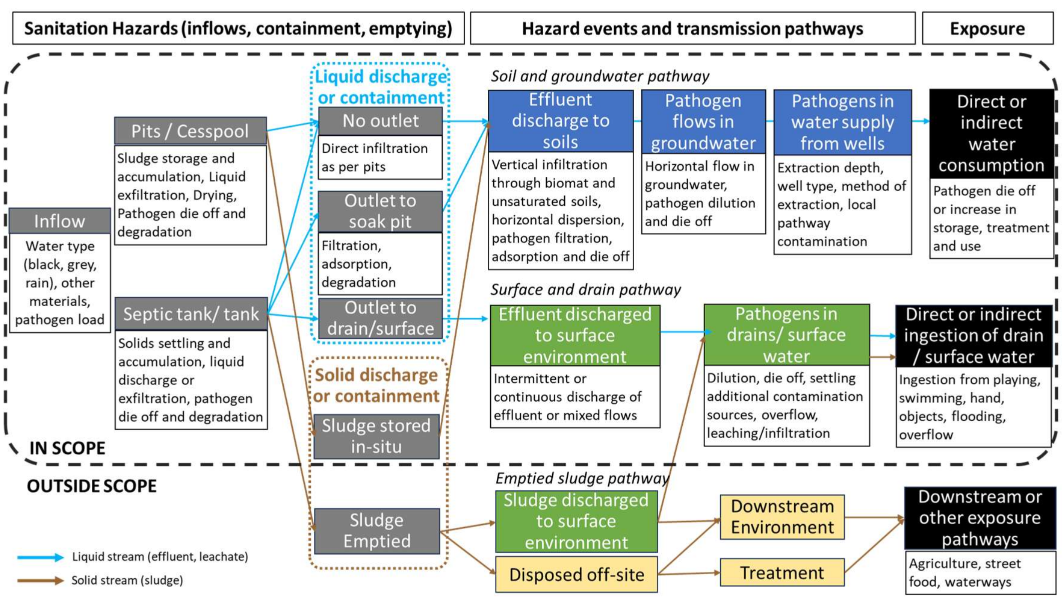

Figure 1.1 *Source, hazard, pathways and exposure to health risks from on-site sanitation, adapted from F-diagram in WHO 2018*

Expanding on this idea of unsafe sanitation as a source of multiple interrelated hazards, Figure 1.1 details the transmission pathways related to hazards at the containment step of the service chain and indicates the transmission pathways within the scope of this thesis. These include hazards due to containment and emptying (on left), the varied and often inter-connected transmission pathways (centre) and exposure risks near the household environment (right). Out of scope are hazards from transport, treatment, disposal, and downstream exposures (e.g. field and skin exposures). Figure 1.1 highlights the complexity of multiple infrastructure arrangements, liquid and solid flow pathways, and processes influencing pathogen discharge from OSS to the environment and transmission to human exposure. Sanitation hazards are characterised by containment types and the arrows track the liquid and solid flows from each system. Hazard events indicate discharge points and transmission routes through groundwater, or drains and surfaces. Exposure pathways included in this thesis focus on groundwater supplies and via drains or surface water. The white boxes summarise the processes and factors affecting the hydraulic and pathogen flows at each step. The diagram provides some background to the complexity of analysing health risks associated with OSS given the multiple and interconnecting transmission pathways and breadth of factors that influence exposure to excreta.

I designed a mixed methods research approach to generate new evidence on the health risks associated with OSSs considering different transmission pathways and varied local contexts through the application of different methods and scales of in-field monitoring in the context of LMICs. The new data and tested methods aim to raise awareness of health risks related to OSS, provide evidence to inform decisions, and identify monitoring and assessment methods that could be integrated into government or development partner monitoring, or replicated in future research in different contexts or scope. The research consists of one qualitative literature review study and three quantitative studies, applying a wide range of methods including environmental sampling, household surveys, sanitation inspections, mapping and statistical analysis. Methods of assessment varied from more complex data collection and analysis methods at a smaller neighbourhood scale to more simplified methods at larger city and national scales.

Recognising that different hazards are critical in different contexts, this research was conducted in locations where the hazards were known to be locally relevant. The research focused on the regions of Asia and Africa, where OSSs are the main type of sanitation, making up over 80% of improved sanitation in Central and Southern Asia and Sub-Saharan Africa (UNICEF and WHO, 2023). The empirical studies that focused on effluent discharges from OSSs focused on Asia, where cultural practices and water availability mean flush toilets are the norm. While both Indonesia and Bangladesh face multiple containment issues, Indonesia was chosen to assess groundwater contamination due to the common use of shallow wells and OSSs in urban areas and concerns over faecal contamination of water supplies (Genter et al., 2022). While in Dhaka, Bangladesh, the site was chosen due to the presence of multiple standard-sized and well-constructed septic tanks in a neighbourhood that provided favourable in-situ research conditions. Furthermore, the poor infiltration capacity of soils in Dhaka mean OSS effluent discharging to drains is a widespread and ongoing issue (Ross, Scott, Blackett, et al., 2016).

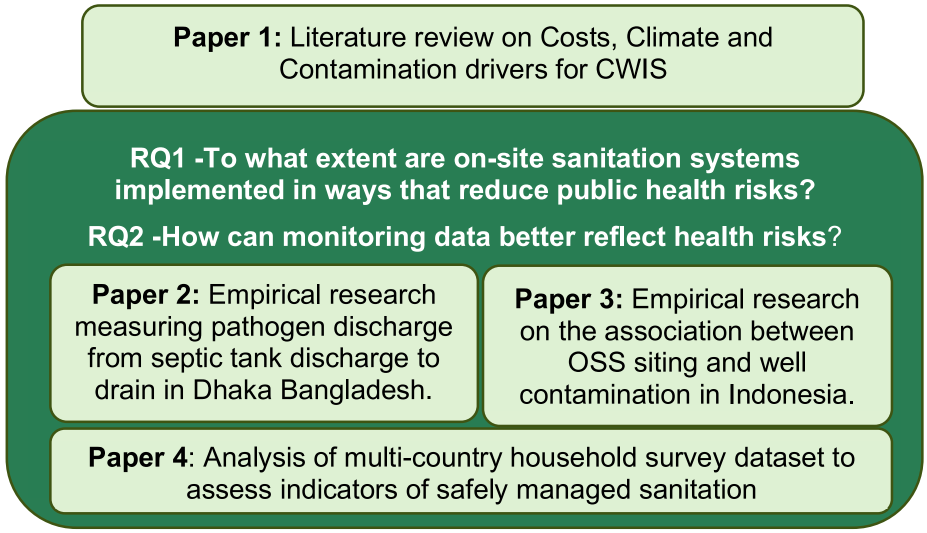

Figure 1.2 *Schematic showing Paper 1 as an overarching literature review and Papers 2, 3 and 4 feed into both research questions*

This section summarises the methods used in the four papers, which are outlined on the following pages and detailed methods are provided in each paper. Figure 1.2 is a summary of the objectives and methods of the four studies. The detailed methods are presented in the chapters of each paper. The first paper included a scoping review of literature to identify the nature and extent of research on how different drivers are informing sanitation investment decisions, which led to the focus of the thesis on the public health driver. This was followed by two in-depth empirical studies that were conducted in low-income urban areas in Indonesia and Bangladesh in Asia as mentioned above. Paper 2 assessed the discharge of untreated excreta to the surface environment and the influence of implementation factors on direct discharge from septic tanks to drains in a low-income neighbourhood in Dhaka, Bangladesh. This research involved the analysis of the presence and concentration of five pathogens and *E. coli,* using qPCR and IDEXX, from septic tank effluent and drain samples and used statistical analysis and quantitative microbial risk assessment (QMRA) to assess the factors affecting concentration and risks of exposure. Paper 3 assessed the association of unsealed OSSs with groundwater contamination in Metro, Indonesia, through census sampling of one neighbourhood, surveying and mapping wells and sanitation facilities with GIS, measuring OSS and groundwater depth, and analysis of repeat well samples for *E. coli* using IDEXX. The association of horizontal and vertical separation of sanitation facilities and wells was assessed using repeat measures statistical analysis, controlling for local and environmental factors. Lastly, the final paper contained a multi-country analysis of survey data from 31,784 households in Asia and Africa to evaluate indicators of health risks for local assessments of safely managed sanitation services.

Ethical approval for the study (ETH20-5620) was assessed by UTS Human Research Ethics Committee and granted on 6 July 2021. Ethics was also granted for the data collection in Paper 2 by the UTS Ethics Committee (UTS HREC REF NO. ETH18-2599) and the International Centre for Diarrhoeal Diseases Research, Bangladesh (icddr,b) scientific and ethical review committees (protocol number PR-19011, 2019).

Paper 1: Costs, climate and contamination: Three drivers for citywide sanitation investment decisions

Research question: How are three potential drivers of citywide sanitation decision-making (public health, sustainability and economic performance) considered in investment decisions, the current state of knowledge about them, and priority aspects to be included in decisions.

Method: Scoping review drawing on academic literature as well as high-quality grey literature, predominantly published between 2015 and 2020, found through systematic literature searches of titles, abstracts and keywords including sanitation and any of decision-making; planning; options; climate; public health; pathogens; costing; or finance. Literature was analysed in terms of their significance to urban sanitation, the state of knowledge and knowledge gaps, the extent to which it is currently considered in decision-making, and priorities going forward. The interconnections between contamination, climate change and costs were analysed and the implications of these interconnections to achieve sustainable and equitable citywide sanitation.

Location, dates: Global English literature, review conducted 2019/2020.

Collaboration: ISF team members Juliet Willetts, Naomi Carrard and Jeremy Kohlitz and PhD co-supervisor Barbara Evans.

Alignment with research questions: This research formed part of the initial conceptualisation of the thesis and informed the research questions and approach by identifying the gaps in evidence on health risks to inform investment decisions. This paper provided initial evidence that OSSs may not be implemented as intended, identified gaps in evidence of health risks, particularly related to pathogens, and concluded that approaches to monitoring health risks did not provide adequate evidence on different sanitation options to inform decisions related to citywide sanitation.

Publication: Frontiers of Environmental Science. 8:130. https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2020.00130

Paper 2: Unsafe containment: Public health risks of septic tanks discharging to drains in Dhaka Bangladesh

Research question: To what extent do 'septic tanks', as currently used in dense low-income areas, reduce pathogen discharge to the environment, considering their design, use and function.

Method: Mixed methods were used to assess the type and implementation of all sanitation facilities and inflows in four residential streets in a neighbourhood in Dhaka, Bangladesh. Methods included household surveys (n=349 households), sanitation inspections (n=173 compounds), sludge depth measurements (n=7 tanks) and analysis of water quality sampled from septic tank effluent (n=18) and open drains (n=33). The site was chosen because the drains only received inflows from the residents assessed and there was no upstream inflow. Water samples were analysed for presence and concentration of Norovirus GII, *Salmonella typhi*, *Vibrio cholerae, Giardia,* and *Shigella* using qPCR, and *E. coli* using IDEXX- Quanti-tray 2000 technique with Colilert-24 media. Data was analysed using SPSS to assess association between septic tank implementation and effluent quality, log reduction in septic tanks, influence of septic tanks on drain quality and potential risk of illness from exposure to drains.

Location, dates: Mirpur slum in Dhaka, Bangladesh. Data collected 2019.

Collaboration: ISF-UTS (Tim Foster, Juliet Willetts), Emory University (Christine Moe, Pengbo Liu), Iccdr,b (Nuhu Amin, Mahbubur Rahman). Research was funded by WSUP.

Alignment with research questions: This study investigated the influence of septic tank implementation on faecal contamination of open drains and the influence of septic tank use on the probability of illness from exposure to contaminated drains. It considered the implementation issues of direct discharge to drains and tanks operating beyond design standards (considering sludge depth and hydraulic retention time). The in-situ monitoring of a range of pathogens beyond *E. coli* in the context of a low-income country aimed to provide new evidence on the releases and performance of septic tanks for different pathogens and how the use and how varied pathogen discharges influences health risks of open drains.

Publication: Published in PlosWater on 19 December 2024. https://journals.plos.org/water/article?id=10.1371/journal.pwat.0000325

Paper 3: Evidence to inform onsite well and sanitation siting criteria: Risk factors associated with well contamination in urban Indonesia

Research question: To examine whether compliance with Indonesian standards for horizontal and vertical separation between OSSs and wells is associated with reduced faecal contamination using repeat measures of *E. coli* during the dry season.

Method: This study assessed whether compliance with the Indonesian sanitation siting criteria was associated with reduced *E. coli* contamination of wells. The criteria require 10m horizontal separation between wells and sanitation systems and 2m vertical separation from groundwater. The sample included an entire neighbourhood in Metro Indonesia, which was sampled (n=131 households) where groundwater was shallow, and almost all households used OSSs and on-premises dug wells or boreholes. A household survey was conducted and all well and sanitation facilities were inspected and mapped using QGIS. Wells (n=94) were sampled three times over two months during the dry season and analysed for *E. coli* concentrations using IDEXX- Quanti-tray 2000 technique with Colilert-18 media. Groundwater depth of dug wells (n=70) was also measured following each water sampling and septic tank depths were measured if accessible (n=31). Using SPSS, GEE binary logistic regression analysis was conducted on the repeat samples to assess the influence of the siting criteria and other sanitation variables on well contamination, controlling for well and environmental variables.

Location, dates: Metro City, Indonesia. Data collected 2021, analysis 2022/24.

Collaboration: PhD supervisors (Juliet Willetts, Tim Foster, Barbara Evans) and partners from Universitas Indonesia (Siti Maysarah, Cindy Priadi). The research was funded through DFAT’s Water for Women project.

Alignment with research questions: The analysis assessed implementation in respect to sanitation siting criteria and the risks associated with contamination of household wells. Other sanitation variables were also assessed based on a detailed inspection and mapping of sanitation facilities to determine whether other sanitation factors were associated with increased risk of contamination. The approach to conduct census sampling, repeat water quality and groundwater depth monitoring, and statistical analysis of repeat measures were methods to overcome several limitations of previous studies that investigated the role of sanitation on well contamination.

Publication: Submitted to IWA Journal of Water & Health on 2nd February 2025.

Paper 4: Indicators to complement global monitoring of safely managed on-site sanitation to understand health risks

Research aim: To evaluate the extent to which consideration of critical exposure pathways through complementary indicators influenced the assessment of safely managed on-site sanitation and in what contexts or conditions indicators may be more or less important.

Methods: The data from health-related household questions were assessed to compare five complementary indicators on health risk with the equivalent global sub-indicators for improved, contained and emptied on-site sanitation. Data came from surveys of 31,784 households in 34 urban and rural districts in Asia and Africa, collected by trained enumerators as part of SNV's sanitation programmes baseline monitoring in 2018–2019. The data from health-related household questions were assessed to compare global sub-indicators for improved, contained and emptied on-site sanitation with five complementary indicators of safety: animal access to excreta, groundwater contamination, overdue emptying, entering containments to empty and inadequate protection during emptying. The prevalence ratio of the association between contextual variables and the complementary indicators being safe or unsafe was analysed using SPSS to inform which indicators or exposure pathways may be most important in specific contexts,

Location, dates: Surveys implemented between 2018 and 2019 in seven countries (Bangladesh, Bhutan, Indonesia, Laos, Nepal, Tanzania, Zambia). Analysis 2023/2024.

Collaboration: PhD supervisors (Tim Foster, Barbara Evans, Juliet Willetts), SNV (Antoinette Kome, Rajeev Munankami, Gabrielle Halcrow, Antony Ndungu). Funded by SNV as part of a multi-year knowledge and learning partnership with ISF-UTS.

Alignment with research questions: Despite being labelled 'safely managed sanitation', the global indicators do not assess five key pathways of faecal transmission (animal access to excreta, groundwater contamination risk, infrequent emptying, entering pits to empty and lack of PPE during emptying). The research provides new data on the prevalence of these risks, considering different sanitation implementation and contexts in seven countries. The research aims to support local or national governments decide whether these additional indicators could be implemented into regular monitoring to improve local assessment of sanitation risks.

Publication: Article was published in npj Clean Water 7.1 (2024): 58.
https://www.nature.com/articles/s41545-024-00353-2

1.2.3 Boundary of research

This section explains the boundaries of the research scope related to the technology, the definition of health risks, the regions covered, and the scope of the analytical approach. While this focus is required for in-depth research, there are many aspects beyond this scope that are also important for sanitation investment decisions and public health. The discussion and the policy implication sections of the conclusion reflect on how these findings interact with or can contribute to broader aspects of sanitation.

Related to sanitation technology, the scope is limited to a focus on OSSs and does not assess risks related to sewerage or decentralised (community scale) systems. Considering the sanitation service chain (see Figure 1.3), the empirical studies (Papers 2 and 3) focused on the step of containment, while Paper 4 also included aspects of access to improved toilets and emptying. Risks associated with transport, treatment, disposal and reuse have not been covered in this research, and they present a range of other possible health risks, particularly for sanitation workers. Figure 1.4 shows the focus of each paper, noting that the empirical research focused on systems connected to flush toilets (i.e. septic tanks and cesspools/wet latrines), although Paper 4 also covered dry pit latrines. Considering the exposure pathways, Paper 2 and 3 focus on water-based exposure pathways via open drains or drinking water, respectively. Paper 4 includes these pathways but also hazards that contribute to exposure via animals, surfaces with flooding and overflow, and the occupational health and safety of sanitation workers.

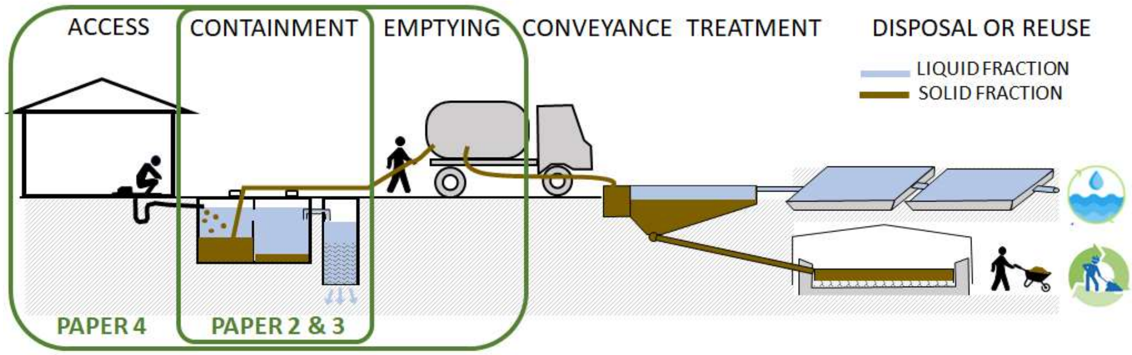

Figure 1.3 *Sanitation service chain for on-site sanitation showing the research focus on the access, containment and emptying steps*

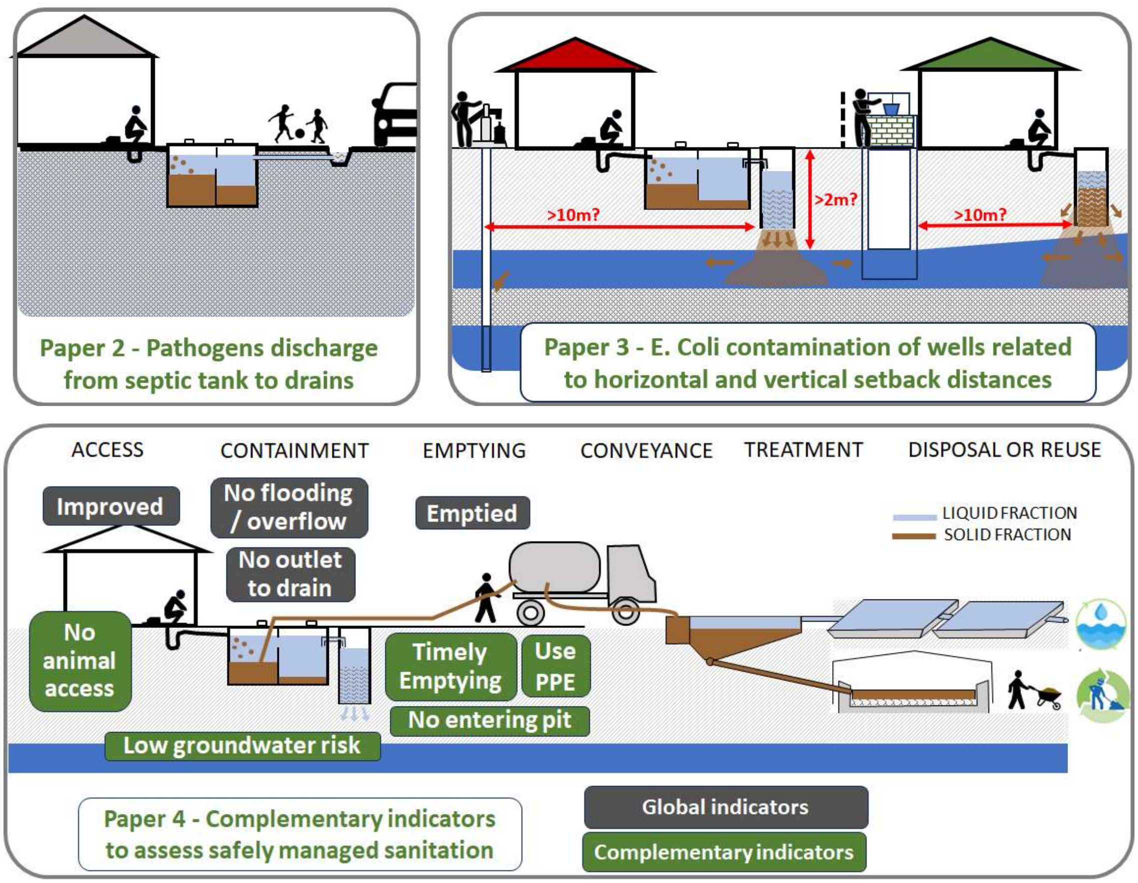

Figure 1.4 *Scope of different papers in relation to the sanitation service chain*

The WHO Guidelines on Sanitation and Health emphasise that poor sanitation poses various health risks beyond exposure to faecal contamination. These include vector-borne diseases, skin and respiratory infections, as well as mental and social well-being issues related to inadequate access or safety (WHO, 2018). This research focuses only on the risk of exposure to faecal pathogens, predominately waterborne, and does not consider broader public health issues. With the focus on an engineering approach to risk, the health aspects of exposure levels, dose-response, population susceptibility or health outcomes are considered out of scope. Paper 2 applies a quantitative microbial risk assessment based on assumptions from local data and literature about exposure, dose-response and probability of illness.

The regional focus is LMICs with two papers focused on Asia (Bangladesh and Indonesia) and one on seven countries in Asia and Africa (Bangladesh, Bhutan, Indonesia, Laos, Nepal, Tanzania and Zambia), see Figure 1.5. Given that context plays an important role in the type of sanitation and nature of risks, it is important to note that the two in-depth studies were both low-income urban areas and the site in Bangladesh was a dense urban slum. Water-flush toilets are predominately used in both countries and the conditions are tropical, with heavy rainfall common. Paper 4 had a broader regional scope including two countries in Africa, rural areas in Bhutan, Laos and Nepal, and the use of sewer and dry pits.

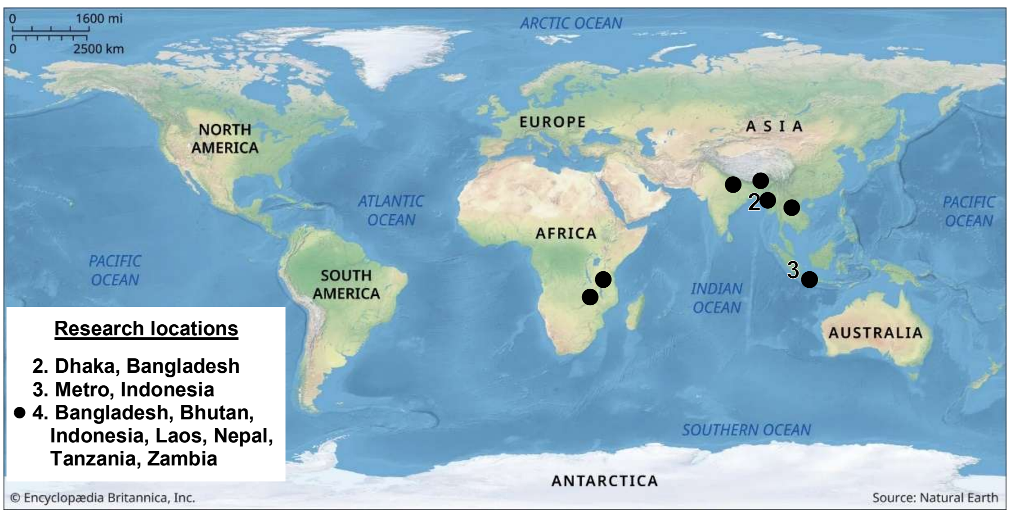

Figure 1.5 *Research locations – seven countries in Asia and Africa*

Lastly, the research focuses on the generation of evidence and monitoring data but not the political economy aspects that support the collection and use of data. While the ultimate aim of the research is that this new evidence can inform decisions, the thesis does not cover the processes involved in sanitation investment decisions, option selection, or the institutional aspects of implementing monitoring and using evidence. Similarly design standards and siting criteria are discussed but with limited focus on the institutional and regulatory aspects that are necessary for enforcement and compliance with standards.

1.2.4 Relevance of research

This section summarises the relevance of the research for science and policy by identifying the areas of original contribution that address the identified research gaps. I also summarise the dissemination of the research to date through conferences and other contributions to increasing awareness of knowledge of this research topic within the WASH and development sector.

1.2.4.1 Relevance to science

Recent literature reviews have highlighted that there is a paucity of data on the pathogen removal and discharge from on-site sanitation. The research that does exist, particularly for septic tanks, comes predominately from high-income countries and often rural or laboratory settings. This research contributes new data focused on the areas where OSSs are most commonly used, and how systems are actually implemented and functioning in-situ. These findings can be compared with existing data from HICs or ideal systems to inform the applicability of existing data to conditions in LMICs or where more data is needed. The evidence from this research can also be used to inform monitoring assumptions, models and tools.

A range of data is needed to understand risks related to sanitation and inform investment decisions. This research includes both detailed empirical data collection and approaches for local- or national-level household monitoring. The empirical studies provide examples of how environmental sampling, sanitation inspections and statistical analysis can be combined to better understand how the physical systems are contributing to environmental health hazards. The methods consider the range of pathways that OSS, and other sources, contribute to public health risks and the importance of assessing system implementation and excreta releases rather than just the presence of sanitation. Given recent advances in technologies to measure pathogens in the environment, including the availability of wastewater surveillance equipment in some LMICs, the approaches to integrate more engineering-based risk assessment to the environmental health monitoring could expand current surveillance to better assess sources of sanitation hazards and options for reducing risks.

1.2.4.2 Relevance to practice

The risks associated with OSSs may be well understood in academia, but there is a clear lack of awareness about the health risks in practice due to ongoing construction and promotion of poorly designed, sited, or operated sanitation systems. The evidence from this research can help increase awareness of the significance of health risks related to sanitation in LMICs and highlight the urgent need for sanitation investments in LMICs to prioritise reducing public health risks. This research also demonstrates the various risks associated with sanitation, which can vary with context and facility type, and that decisions must be made about the level of acceptable risk. Given the various steps in the sanitation service chain and levels of service, sanitation investments are likely to make progressive improvements that can reduce different risks for different populations. Quantifying health risks of pathogen discharges from septic tanks can inform whether the incremental health benefits from improvements (i.e. upgrading direct discharge to a tank, or emptying tanks) are justified investments. While the complementary indicators can help to identify whether national monitoring would benefit from going beyond the global definition of ‘safely managed sanitation’ to identify and address critical local risks such as groundwater contamination or unsafe emptying practices.

By focusing on the containment step of the on-site sanitation service chain, the research draws attention to the releases of excreta and health risks at the start of the chain, in the vicinity of the household and neighbourhood. While recent projects have focused on improving the methods for emptying, transport and treatment methods, this research emphasises the importance of building, operating and managing OSSs considering the context in which they are used. The thesis points out the need for improvement in standards, technical solutions and also the practice of development partners to facilitate this. The way OSSs are discussed and presented can also be improved, as the term OSS encompasses a range of system types that differ in function and risk, based on their location and usage. Important issues, such as septic tanks discharging directly to drains, may be affected by misleading images and language that fail to reference the critical subsurface infiltration step. Therefore, this research highlights the diversity in system implementation and associated risks across different contexts, with the goal of promoting increased monitoring at different scales. This approach can ensure sanitation improvements are tailored to the specific systems and risks present in each context.

1.2.4.3 Contribution to sector knowledge

The research included in this thesis was presented at several conferences through platform presentations or as part of multi-stakeholder workshops. In addition to these presentations, I also contributed to global expert groups including the WHO/UNICEF

Joint Monitoring Programme panel for monitoring water quality and sanitation and the WHO and UNICEF Global Sanitation Summit in Nepal and led the session on data systems. These activities have shared the findings with government and development partners that may not engage with published journal articles, while also enabling me to incorporate feedback into the research findings and application to practice.

Table 1.2. *Summary of conference presentations and workshops*

Conference	Presentation or workshop title
Indonesia Government workshops	Presentation by supervisor Tim Foster on the findings of Paper 3, coupled with broader research by ISF-UTS on self-supply at a national workshop on Risks to Groundwater Quality in January 2024.
	Presentation of preliminary findings (Paper 3) by local research partner Universitas Indonesia to the Metro government in October 2022.
IWA Water and Development Congress, Kigali, 2023	Platform presentation of Paper 4. The presentation was titled: “Is it safe? Role of global and complementary indicators to inform progress of safely managed on-site sanitation”.
IWA WaterMicro, 2023	Findings of Paper 2 titled “Septic tanks discharging to drains – a hidden health risk and not a safe sanitation solution” presented by supervisor Tim Foster.
UNC Water and Health Conference, 2021	Presented in a joint stakeholder workshop on “Understanding the Pathogen Flows Associated with the Sanitation Practices in Urban Communities”. Co-hosted in partnership with Emory University, UNC and icddr,b and included a presentation of Paper 2.
World Water Week, 2021	Facilitated a joint stakeholder workshop titled “Equitable and resilient urban sanitation services: framing agenda for action”. Co-hosted with WSUP, SNV, WHO and Emory and included predominately Paper 2 but also aspects of Paper 1.
FSM6 Conference, 2021	Presentation (Paper 2) – “Improving containment in dense low-income areas: Septic tanks discharging to drains are not a safe solution”.
	Workshop (Paper 1) – “Spotlight on Citywide Inclusive Sanitation and Climate Resilient Sanitation in LICs”.
UNC Water and Health Conference, 2020	Presentation (Paper 2) – “What is ‘Quality’ Sanitation? Investigating Service Standards and User Experience in Rural and Urban Settings”.

1.3 Thesis outline

The thesis comprises a literature review, which includes the first paper, followed by the three quantitative research papers, a discussion section that presents the combined findings in relation to the research questions, and a conclusion that reflects on the significance and way forward. The contents of each chapter are outlined below.

Part II – Literature review

Chapter 2 – The literature review first presents a brief history of changing drivers for sanitation, followed by **Paper 1, "Costs, climate and contamination: Three drivers for citywide sanitation investment decisions",** which was published in 2020 and is supplemented by a summary of recent research.

Chapter 3 – The literature review then focuses on the public health impacts of sanitation and the value of a public health engineering approach to research. This is followed by the justification of the focus on on-site sanitation, a summary of research on health risks associated with on-site sanitation, and current engineering and public health approaches to monitor health risks, concluding with a summary of research gaps.

Part III – Results

Chapter 4 presents **Paper 2, "Unsafe containment: Public health risks of septic tanks discharging to drains in Dhaka Bangladesh"**. The article presents the empirical research on pathogens discharged from septic tanks to open drains in Bangladesh.

Chapter 5 presents **Paper 3, "How do sanitation siting criteria in urban areas relate to well contamination in shallow groundwater in Indonesia"**. The article presents an analysis of the influence of Indonesian sanitation siting criteria on *E. coli* contamination of wells in an urban neighbourhood in Indonesia.

Chapter 6 presents **Paper 4, "Indicators to complement global monitoring of safely managed on-site sanitation to understand health risks"**. The article presents five complementary indicators for monitoring health risks of sanitation and, through a large household survey dataset, assesses how these compare to global indicators for safely managed sanitation.

Part IV – Discussion and conclusion

Chapter 7 – Discussion summarises the main findings across the studies and how the combined research responds to the two research questions, drawing conclusions from across the studies. The research limitations are presented considering scope and methods.

Chapter 8 – Conclusion summarises the overarching findings, reflects on the contribution to knowledge and practice, links back to the implication of the findings on the other drivers of sanitation, and presents ideas for future research.

Appendix

Appendices include supplementary material for each of the included publications.

PART II
LITERATURE REVIEW

2. Public health driver for sanitation

- **Evolution of drivers for sanitation**
- **Paper 1: *Costs, climate and contamination: Three drivers for citywide sanitation investment decisions***
- **Updates since publication**

2.1 Introduction

The review starts with a historical perspective on the drivers for sanitation and the loss of a focus on public health. This broad context then sets the scene for Paper 1, titled "Costs, climate and contamination: Three drivers for citywide sanitation investment decisions", which reviews the literature to assess the current state of knowledge and how public health, climate change and economic performance are considered in sanitation decisions. As this paper was published in 2020, I provide a brief update on advances in research on these three drivers. The subsequent chapter of the literature review then focuses on the health issues associated with sanitation, the risks specific to on-site sanitation and current approaches to monitoring health risks of sanitation.

2.2 Evolution of sanitation drivers: Shifting away from public health

There are multiple drivers for improving sanitation, and while public health is historically perceived as a key objective, more recently, more attention has been paid to other drivers. This section presents the evolution of sanitation drivers, including environmental, economic, private sector engagement, resource recovery and climate change, focusing on why there has been a shift away from public health objectives.

Drivers refer to the factors influencing why to invest in sanitation and how investments are targeted. This thesis predominately focuses on the influence of drivers on how sanitation is improved from a technical lens with less focus on the role of health as a rationale for investment and political engagement in sanitation progress, which have been the focus of other reviews (Brugger, 2021; Cummings et al., 2024; Northover et al., 2016). Several papers have reviewed these shifting drivers, each adopting a different lens for the review. For example, Brugger (2021) applied a territorial political economy perspective, Kennedy-Walker et al. (2014) investigated the influence of Kalbermatten's planning approach, Rosenqvist et al. (2016) focused on the perception and discourse of sanitation from a development perspective, Lofrano and Brown (2010) focused on wastewater, while Angelakis et al. (2023) reviewed the historical developments in the pre-modern era. The following section summarises the commonly reported periods from the modern era, most closely aligned with the periods presented by Brugger, focusing on how the different drivers influence sanitation infrastructure and services.

Industrialisation 1860–1950: Public health was commonly recognised as the driver for the revolution of sanitation in alignment with the Industrial Revolution in the period of 1860–1950 (Brugger, 2021). The realisation that sanitation systems were contaminating the water supply and contributing to illness led to significant advances in urban sanitation, with various studies documenting the transition to flush toilets and sewers in Britain, France and Germany (Lofrano & Brown, 2010). Large cholera outbreaks that affected entire populations drove these advances, informed by a medical science and civil engineering knowledge base (Brugger, 2021). This period is sometimes referred to as the ‘Sanitation Revolution’ and was associated with the widespread construction of toilets and sewers in HICs and significant improvements in public health. The sanitary advances in this period are often reported as one of the most important health achievements of the past 200 years (Mara et al., 2010).

***Figure 2.1** Timescale of shifting drivers for sanitation*

Environmental 1950–1990: Next came the driver to protect the environment due to the heavy pollution caused by the direct discharge of the sewers to rivers, which were built under the assumption that dilution would adequately treat the pollution (Lofrano & Brown, 2010). Major issues in river quality and ecological disasters (i.e. mass fish deaths and dead lakes) in the UK led to the development of wastewater treatment and environmental discharge standards based on a natural science and environmental engineering knowledge base (Brugger, 2021). This shift to an environmental focus was also evident in the USA, where the practice and profession of environmental engineering separated from public health in the latter half of the 20th century to the newly created Environmental Protection Agency (Gelting et al., 2019).

Economic and privatisation 1990– ongoing: With the increasing cost of expanding sanitation and wastewater treatment infrastructure, there was a shift to engage the private sector in the construction and management of sanitation services. Given that public and water ecosystem health were seemingly under control, there was increased pressure to reduce taxes and improve the management of sanitation services (Brugger, 2021). However, since 2000, in many cities, the responsibility for wastewater and sanitation services has returned to the municipality (Rosenqvist et al., 2016). More recently, in LMICs, there has been increasing recognition of the role of the private sector in providing emptying services and new drivers to increase the safety and formalisation of these services.

Circular economy 2008– ongoing. The increasing costs of managing wastewater and faecal sludge also led to the increased attention that waste could be a valuable resource. This aligned with increasing attention to circular economies and the opportunity to close the resource cycle for water, nutrients and energy outputs from sanitation (Brugger, 2021). Wastewater discharge standards have shifted from protecting the environment to reducing pathogens to increase reuse potential (Lofrano & Brown, 2010; Schellenberg et al., 2020). Resource recovery was also a driver for the above-mentioned entrepreneurship and economic perspectives, with reuse promoted as an opportunity for cost recovery. The potential for revenues from the 'sanitation market' was promoted to entrepreneurs and the private sector. This led to innovations in toilet technologies, such as EcoSan toilets, container-based systems, or high-tech solutions, funded through the Reinvent the Toilet Challenge by the Gates Foundation. Innovations are also emerging for emptying technologies, recovering resources from waste, and associated business models.

Climate change 2020 – ongoing. Over the past five years, the sanitation sector has rapidly increased its engagement with climate change, reflected in an increase in research, conference topics, policies, and its inclusion in the climate agenda. As noted in Paper 1 below, before 2020, climate change was considered an immediate priority due to a focus on service improvements. Section 2.4 summarises the shifts in research, policy and finance that have increased prioritisation of climate resilience and mitigation in sanitation investments and raised awareness of the need to address the increasing risks of poor sanitation in a changing climate.

This history highlights the shift away from public health to prioritise other objectives and outcomes of sanitation services. While the different drivers have all brought valuable advances to sanitation services, the changes in drivers mainly stemmed from the progress achieved in high-income countries due to the widespread coverage of sewerage and reductions in public and environmental health issues. The same progress did not occur in most low-income countries, where there are significant gaps in sanitation services and outbreaks of waterborne diseases remain common (Angelakis et al., 2023; Lofrano & Brown, 2010). In contrast to the population-wide health crises that drove change in HICs during the sanitary revolution, the health risks from sanitation in low-income countries tend to only affect some parts of the population as modern infrastructure (i.e. cars, private compounds, water treatment) mean the higher-income households may be able to avoid exposure to polluted public spaces and exposure is more a private than public issue (Brugger, 2021).

These reviews (Angelakis et al., 2023; Lofrano & Brown, 2010; Rosenqvist et al., 2016), highlight the benefit of looking at history to inform decision-makers on the different perspectives and approaches to improve sanitation services in the future. These shifts in drivers are often associated with a shift in attention to specific technologies or approaches to sanitation that, at times, move away from ensuring they address public health objectives. While these alternative objectives are valuable, they should not mean that health objectives are demoted. Therefore, this thesis aligns with Kalbermatten's principles described in Kennedy-Walker et al. (2014), that health should be a primary objective in sanitation planning and decisions.

2.3 Paper 1 – Costs, climate and contamination: Three drivers for citywide sanitation investment decisions

Paper 1 was published in *Frontiers in Environmental Science* on 11 August 2020 as part of a special issue on citywide sanitation. It summarises the literature on three potential drivers of citywide sanitation decision-making – public health, sustainability and economic performance via the three proxies of contamination, climate change and costs. It examines the importance of each driver and proxy, how they are considered in investment decisions, the current state of knowledge, and the priority aspects to be included in decisions.

Since this article was published in 2020, in the section after the paper I present a summary of relevant research and practice updates since publication.

frontiers in Environmental Science

REVIEW
published: 11 August 2020
doi: 10.3389/fenvs.2020.00130

Costs, Climate and Contamination: Three Drivers for Citywide Sanitation Investment Decisions

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Significant progress is needed, in both large cities and small towns, to meet the ambitious targets set at international and national levels relating to universal access to safely managed sanitation. There has been increased recognition in the urban sanitation sector that in rapidly growing cities, there is unlikely to be a single centralized sanitation solution which can effectively deliver services to all demographics, and that heterogeneous approaches to urban sanitation are required. At the same time, due to competing investment priorities, there is a greater focus on the need for sanitation investments to address multiple objectives. However, calls for more informed sanitation planning and a more dynamic and disaggregated approach to the delivery and management of sanitation services have had limited impacts. This is in part due to the complexity of the drivers for sanitation investment, and the difficulties involved in identifying and addressing these multiple, often conflicting, goals. This paper examines three potential drivers of citywide sanitation decision-making – public health, sustainability and economic performance – via the three proxies of contamination, climate change and costs. It examines the importance of each driver and proxies, how they are considered in investment decisions, the current state of knowledge about them, and priority aspects to be included in decisions. At present, while public health is a common driver for improving sanitation, there are significant gaps in our understanding of fecal contamination spread and exposure, and how to select sanitation solutions which can best address them. Climate change is sometimes seen as a low priority for the sanitation sector given the immediacy and scale of existing challenges and the uncertainty of future climate predictions. However, potential risks are significant, and uninformed decisions may result in greater costs and increased inequalities. Cost data are sparse and unreliable, and it is challenging to build robust cost-effectiveness analyses. Yet these are needed to compare citywide options based on least-cost over their full life cycle. This paper provides insights into how existing evidence on contamination, climate change and costs can inform decisions on sanitation investments and help chart a sustainable way forward for achieving citywide services.

Keywords: urban sanitation, decision-making, contamination, climate change, cost-effectiveness, wastewater, sustainability

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INTRODUCTION

The re-emergence of a citywide perspective on sanitation has focused much-needed attention on sustainable solutions that consider the full sanitation service chain for the entire urban population. This perspective echoes many earlier calls for a radical shift from business as usual to address the inequalities, inadequate coverage and sustainability issues of current poor sanitation in many low- and middle-income countries (LMICs) (e.g., Kalbermatten et al., 1982; Wright, 1997). Globally, one billion people in urban areas are without even basic access to sanitation, considered a basic human right, and inequalities persist, with an increasing gap in access between the richest and poorest urban households in 30% of countries (UNICEF and WHO, 2019). An estimated 53% of the global urban population does not have safely managed sanitation (UNICEF and WHO, 2019), reflecting numerous failures across the service chain and resulting in the discharge of untreated fecal waste across the urban environment (Peal et al., 2014). This situation disproportionately affects poor and marginalized groups (UNICEF and WHO, 2019).

Urban sanitation specialists have long recognized that to achieve citywide sanitation there needs to be a shift away from fixed conventional sanitation technologies toward planning approaches that incorporate a range of solutions to address sanitation in ways which are disaggregated, both geographically across the city and along the sanitation value chain (Wright, 1997; BMGF et al., 2017). Yet the persistent focus of technicians and investors on centralized sewerage systems has resulted in investments concentrating on small, often wealthier, areas of cities, with low-income and challenging areas left with sub-standard services (McGranahan, 2015). Illustrating this point, a recent assessment of the outcomes of investment by development banks found that between 2010 and 2017, banks invested 20 times more in sewerage than in fecal sludge management (FSM) despite the much larger populations serviced by onsite systems (Hutchings et al., 2018). While FSM has received growing attention, onsite and centralized options are often considered independently of each other, without an understanding that combined solutions are the likely way forward in most cities (Hawkins et al., 2013). There is a growing consensus that achieving 'sanitation for all' requires a mix of different contextualized solutions that embrace various scales of technologies and services (Lüthi and Sankara, 2018), and that inequalities in exposure to fecal waste must be actively monitored and progressively reduced (UNICEF and WHO, 2019).

Shifting from business as usual requires improved decision-making frameworks to assist in selecting appropriate investments that balance economic, public health and environmental objectives (WHO, 2018). While these three overarching objectives are often said to drive sanitation investment, it is not always clear how the options considered will contribute to achieving each objective (Kennedy-Walker et al., 2014). In many cases, competing or interlinked objectives are brushed over or only briefly considered. For example, even economic performance, which is usually explicitly examined in development bank operations, is rarely used to compare and prioritize different sanitation delivery options. It is even rarer to see an explicit discussion of the relative importance, for example, of public health, economic performance and sustainability when sanitation options are being prioritized. This is in part due to the lack of requisite data and the absence of institutions with the ability to balance multiple, often conflicting, drivers of investment.

To illustrate the challenges and opportunities inherent in moving toward a more nuanced approach to decision-making, this paper examines contamination, climate and costs as critical lenses for considering the public health, sustainability and economic dimensions of citywide sanitation. These three areas were identified as traditional and emerging drivers that in practice are not being adequately addressed in decisions on citywide sanitation. While investment decision-makers may recognize the importance of these three areas, they may fail to consider them for a number of reasons, including: uncertainty about how to practically include different drivers in option comparisons (fecal contamination, climate), the low priority they assign to these drivers (climate, at times fecal contamination), and inconsistent or limited data and approaches for analysis (costs, contamination). As detailed in the following sections, recent publications have also identified contamination, climate and costs as requiring greater attention. The World Health Organisation (WHO) has reaffirmed that widespread fecal contamination, particularly in low-income urban areas, means that the public health objective for sanitation requires renewed attention (WHO, 2018). Various authors (World Bank, 2011; Oates et al., 2014; ISF-UTS and SNV, 2019; UN Water, 2019; WHO, 2019) have called for climate resilience to become an integral part of decision-making frameworks and implementation approaches. Finally, a recent review of the costs of urban sanitation highlights data gaps in cost reporting and life cycle costings (Daudey, 2018) pointing to inadequate attention to this dimension. This article extends existing analyses by synthesizing a broad set of recent literature and identifying how the three drivers may be better considered when developing citywide services.

This paper reviews the English language literature and draw on both academic literature as well as high-quality gray literature, predominantly published in the last five years, found through systematic literature searches of titles, abstracts and keywords including sanitation and any of: decision-making; planning; options; climate; public health; pathogens; costing; or finance. We discuss each of the three areas in terms of its significance to urban sanitation, the state of knowledge and knowledge gaps, the extent to which it is currently considered in decision-making, and priorities for increasing the attention given to each issue. Recognizing the challenge of balancing these multiple drivers, we also identify interconnections between contamination, climate change and costs, and the implications of these connections for achieving the overarching objectives of sustainable, equitable citywide sanitation.

CONTAMINATION

Given the central aim for sanitation to prevent human exposure to disease, and the wide evidence base concerning the burden of disease related to poor sanitation (Freeman et al., 2017; Prüss-Ustün et al., 2014 and Pullan et al., 2014), this section argues for greater consideration of fecal contamination in sanitation decision-making. Although health has previously been an incentive for prioritizing sanitation, there is little evidence that health is central to long-run investment planning for sanitation in many LMICs (Cummings et al., 2016). The health and economic impacts of poor sanitation are often poorly understood and "invisible," so sanitation tends to be seen as a technical engineering task undertaken in formal areas of a city (Cummings et al., 2016). Indeed, mainstream approaches to the planning and design of sanitation systems reflect this framing, and typically focus on the protection of downstream waterways by instituting environmental discharge standards, often without explicit consideration of pathogen removal (Mills et al., 2018). Even when discharge standards exist; their enforcement is limited and political will is needed to regulate and enforce pollution control measures (UN Water, 2017; WHO and UN Habitat, 2018). Whilst chemical contamination, for example by nitrates, heavy metals and other emerging contaminants, is relevant for public health (Cronin et al., 2007; WHO, 2015; UN Water, 2017), in this paper focus on fecal contamination. This is because of its significance for achieving genuinely 'safely managed' citywide sanitation in LMICs, as demanded by the Sustainable Development Goals (SDGs), and also because it acts as a useful proxy for the effectiveness of urban sanitation systems in interrupting transmission pathways for infectious excreta-related diseases.

Understanding fecal pathogen contamination in urban areas is particularly important in cities and towns with low levels of effective sanitation infrastructure and services. Low levels of access to sanitation are associated with an increased prevalence of disease, particularly diseases that continue to inflict a heavy burden in low-income settings, including diarrhea, soil-transmitted helminth infections, trachoma, cholera and schistosomiasis (Speich et al., 2016; Freeman et al., 2017). In locations with high prevalence rates of infectious disease, pathogen concentrations discharged to sanitation systems or into the environment are correspondingly high, particularly during outbreaks (Lusk et al., 2014). The risk to human health is not only driven by pathogen occurrence but also by their persistence in the environment, the presence of vectors or intermediate hosts, and the level of infectivity of individual pathogens (Aw, 2018). In addition, several diseases such as pathogenic *E. Coli*, salmonellae, and shigella have low infectious doses (e.g., can cause infection in humans with fewer than 20 organisms), whilst they are present in much higher concentrations in wastewater (e.g., more than 10,000 organisms/L) (Lusk et al., 2014). Pathogens that are discharged across the urban environment can be transmitted through multiple exposure pathways, including through contact with drain water, surface water or flood water during activities such as playing, washing and bathing, and through food pathways (Wang et al., 2017). When assessing the potential risks associated with different sanitation systems in decision-making, these numerous exposure pathways and high persistence must be considered. There is limited information about the relative importance (in terms of hazard and exposure) of the multiple sources of fecal waste discharged to the environment across the sanitation chain (for example from open defecation, overflowing pits, discharge of effluent to drains or dumping of sludge). A clear understanding of existing knowledge and knowledge gaps is critical, and in this section we review the status of knowledge related to different sanitation systems and approaches to assessing risks.

On-site sanitation systems are the dominant type of sanitation in urban areas in low- and middle-income countries (UNICEF and WHO, 2019). Confusion abounds regarding definitions of onsite sanitation systems. Key distinctions are frequently conflated. In relation to contamination, the main distinction is between lined tanks and partially lined tanks that are effectively sealed (often erroneously described as 'septic tanks'), and systems which are designed for infiltration of liquid fractions into the ground surrounding the tank.

Starting with septic tanks and sealed tanks that are often described as septic tanks, WHO (2006) note that pathogen removal in septic tanks is poor. Authors variously suggest a treatment effectiveness of 0–2 log removal of pathogens, with several suggesting 0.5 log removal (Feachem et al., 1983; Stenström et al., 2011). As such, septic tanks alone are not considered to be a significant barrier against pathogen transmission, and it is recommended that they discharge to a properly designed and sited soil absorption system (Adegoke and Stenstrom, 2019). Adegoke and Stenstrom (2019) research also notes that treatment effectiveness assumes that the septic tank is operating as it is designed to, that it has at least two chambers and that it is regularly emptied of sludge to ensure adequate hydraulic retention time. Often these conditions are not met, and in these cases treatment effectiveness is unknown. WHO (2018) suggests that poorly designed or constructed onsite systems are not expected to reduce the likelihood or severity of exposure to hazardous events. Large numbers of such sealed tanks discharge directly to surface water bodies and drains, resulting in a direct risk of exposure (Peal et al., 2014). In addition, most studies examining pathogen removal from septic tanks have been conducted in high income countries where high water use and connection of both blackwater and graywater to sanitation systems result in lower pathogen concentrations than those typically seen in LMICs. One factor compounding misperceptions by sector practitioners about pathogen removal is that removal is often reported arithmetically rather than using logarithmic scales, which are more appropriate when dealing with large numbers. This can mask the high numbers of excreted pathogens that remain after primary onsite treatment. For example 99% pathogen removal is equivalent to 2 log removal, so with excreted pathogen concentrations potentially 9–10 log, after 99% removal the effluent may still contain 7 log pathogen concentrations (Mitchell et al., 2016).

Overall, there is a paucity of literature on the fate of pathogens in effluent from onsite systems as it enters the environment (e.g., into soil, groundwater, drains, etc.) and the magnitude of related public health risks (WHO, 2018). Despite this, current mainstream approaches to improving sanitation in LMIC frequently focus on emptying and treatment of fecal sludge, with more limited attention given to the construction quality of onsite and offsite systems and to the pathways the liquid portion of the waste may take in an urban environment (Mitchell et al., 2016; Peal et al., 2014). Further, while there is known variation in the fate of different pathogen types (including viruses, bacteria, protozoa and helminths) in onsite systems and the environment given their different sizes, properties and characteristics (Mitchell et al., 2016), there is limited information available on their relative inactivation and persistence under different environmental conditions (Murphy, 2017). Finally, there is a knowledge gap regarding the partitioning of different pathogen types between the sludge and effluent in onsite systems.

With minimal pathogen removal in onsite systems, the effluent presents significant risks to health. We discuss this firstly from a groundwater contamination perspective, and then from the perspective of surface water and drains. Recent WHO (2018) design guidelines require that wet pit latrines only be used in areas of deep groundwater, and that if groundwater is used for domestic water supply then: pits should be located at least 1.5 m above the water table; 15 m horizontally down-gradient from the water supply; no graywater should be added; and septic tanks should discharge to a soak pit or leach field. However, appropriately designed soak-aways and absorption trenches are typically missing in dense urban areas or may be used in unfavorable groundwater conditions (high water table, highly porous soils) (World Bank, 2015; Peal et al., 2020). In addition, research has found that the travel distance of pathogens varies widely, questioning the validity of generalized separation guidance between pits and wells (Williams and Overbo, 2015). Recent studies in the United States have shown that the number of septic tanks in an area has a significant influence on the level of human fecal pollution in groundwater (Sowah et al., 2017). There are also concerns that pathogens from pit latrines can reach groundwater of varying depths, with a review of the existing literature noting that viruses in particular can travel long distances. Whereas protozoa and helminths could be expected to be retained by the soil beneath pits (Orner et al., 2018), viruses have been found in groundwater tube wells up to 50 m away from toilets (Verheyen et al., 2009). However, most research relating to the contamination of groundwater tube wells fails to distinguish between contamination from toilets via the groundwater and direct contamination of the tube wells from the surface. The significance of groundwater contamination will vary by city. Importantly, contamination of shallow groundwater from non-toilet sources is usually high, and in general the use of shallow groundwater for urban water supplies is not recommended, though its use is a reality in many contexts. In some locations where piped water is available, both fecal and other contamination may be a minor consideration. In other contexts, for instance in Indonesia where 32% of the two lowest quintiles in urban areas use on-premises self-supplied groundwater (BPS, 2018), such contamination may be a cause for concern, requiring the application of related tools to assist in risk assessment (e.g., see SanitContam in Krishnan, 2011). However, it is worth mentioning here that the complete replacement of sanitation systems that rely on leaching (to avoid fecal contamination of the surface environment) may need to be weighed up against options for water supply improvements to reduce groundwater use.

Where infiltrating pit soak-aways or leach fields are impractical, there is little evidence of the widespread adoption of safe alternatives (which would primarily focus on either the provision of solid-free sewage to convey liquid effluent to treatment, or the adoption of alternative technologies such as sewerage or container-based sanitation). The most common approach is to discharge pits and tanks directly to water bodies or open ground. In many locations, discharge from septic tanks or pit latrines to drains or waterways presents a significant hazard; often there is inadequate space for a soak pit or the groundwater level is too high to permit infiltration. The Sanitation and Health Guidelines (WHO, 2018) consider any containment units, including septic tanks, that are connected to a drain or a water body are unsafe due to the exposure hazard of the effluent. Despite this, at present the management of liquid waste from containment systems is not included in common FSM solutions and diagrams (see Parkinson et al., 2014; Strande et al., 2014) and insufficient consideration is given to the health risks of onsite systems in dense urban areas (Satterthwaite et al., 2015). WHO (2018) argues that there is currently a lack of options for improving containment and reducing the exposure to effluent from onsite systems discharged to open drains. Indeed, it is highly probable that additional effluent conveyance and treatment, which is a considerable additional cost (Tilley et al., 2014), might be needed to prevent exposure.

Anaerobic baffle reactors (ABR), which have a similar primary treatment function to septic tanks, also achieve limited pathogen removal. ABRs are commonly installed in decentralized wastewater treatment systems in LMICs. While the retention time is longer than for septic tanks, research in South Africa found approximately 1 log removal for bacteria, viruses, and protozoa, and about 2 log removal for helminths (Foxon, 2009). Further treatment is necessary to meet most national effluent standards (Tayler, 2018). Analysis of the performance of 50 small-scale sanitation systems in South Asia, including ABR-based systems and more advanced technologies, found that almost all systems consistently failed to meet microbial water quality standards, with no improvement in systems fitted with a disinfection step (EAWAG, 2018). Most of the systems in this analysis had effluent fecal coliform concentrations of 10^4–10^6 MPN/100 mL. In line with this, WHO (2018) guidelines state that the effluent and sludge from ABR and anaerobic filters have high pathogen levels and require further treatment. However, these systems often discharge directly to local drains or waterways. Constructed wetlands provide a simple additional pathogen reduction option, but they require additional land area (Tayler, 2018).

Off-site sewerage may avoid many of the above challenges, but it does not necessarily solve all contamination issues as leakage can occur during conveyance, and even with advanced treatment processes some wastewater effluent still contains high levels of pathogens (WHO, 2018). Leakage can happen due to: misconnections (where a sanitary or graywater sewer pipe is connected to a surface drain unintentionally); structural deficiencies resulting in exfiltration into groundwater supplies; flooding events resulting in combined sewer overflows entering surface water; or sanitary system overflows whereby sewage flows into stormwater systems due to clogged or broken pipes, infiltration, or power failures, and results in discharge of untreated wastewater into surface water bodies (Williams and Overbo, 2015). Most national wastewater effluent standards do not include pathogen targets (WHO, 2018; Tayler, 2018), despite the continued exposure risk if the receiving waterway is used in agriculture or for recreation. Similarly, the target SDG 6.2 also considers secondary treatment to be safe (WHO, and UNICEF, 2017) despite the fact that pathogen reduction in accepted technologies is typically inadequate (WHO, 2006). Ultimately, decisions about the level of treatment must consider the downstream exposure risk, as proposed in the draft SDG definitions (WHO, 2016) or as suggested in sanitation safety planning (SSP) (WHO, 2015).

Container-based sanitation (CBS) is a recent development that may provide opportunities to prevent contamination of groundwater and surface water, particularly in dense low-income settlements. In general, these are mostly urine-separating toilets in which fecal matter is collected in a bag or container (replaced regularly by a local enterprise and taken away for further fecal sludge treatment) and diverted urine is typically disposed of in drains or sewers, or infiltrated into the soil (Mara, 2018; World Bank, 2019). In Cape Town, South Africa, a utility is operating a related low water-use system with a 20 L container collected twice weekly then emptied, cleaned and disinfected mechanically at the local sewage treatment plant (Willetts, 2019). Yet CBS and onsite systems requiring pits or tanks to be emptied all potentially create significant risks to sanitary workers, and this issue requires proactive management (Mackinnon et al., 2019; World Bank, 2019).

The risks to public health arising from inadequate sanitation are driven by both the extent of the hazard that enters the environment and the probability of human exposure to that hazard. In addition to understanding the source and ability of different 'technologies' to reduce contamination of the urban living environment, it is important to understand the *exposure* and how this varies across a city context, including related inequalities. Low-income households are at greater risk from exposure, as they are more likely to be in areas affected by sewage and septage overflow during floods (Hawkins et al., 2013).The identification of locally important key fecal transmission pathways, and an understanding of a person's full exposure to fecal pathogens, can provide valuable information for the prioritization of interventions (Robb et al., 2017; WHO, 2018; Wang et al., 2018). Various studies have found that exposure and health risks are associated not only with an individual's sanitation but also the sanitation of their communities (Hunter and Prüss-Ustün, 2016; Wolf et al., 2019). For example, in Timor-Leste, although only 7% of the urban population uses toilets that flush to an open drain, 55% live in communities where at least one household uses a toilet that flushes to an open drain, potentially exposing many households in the neighborhood to pathogens (UNICEF and WHO, 2019). Equally, not all fecal contamination may be an exposure risk. For example, if shallow groundwater is not used due to alternative available, affordable and convenient drinking water options, then groundwater contamination may carry a lower risk. A citywide approach also calls for the exposure risk of all population groups to be addressed, including at-risk groups such as sanitation workers and farmers who are exposed to dumped sludge or untreated wastewater (Farling et al., 2019).

One of the major challenges in assessing contamination and health risk is the complexity of the science involved. Several efforts have been made in recent years to create simple assessment tools and approaches that can facilitate a general conversation about the relative scale of risks and the consequent investments that could be prioritized to reduce such risks. Since 2006, WHO has been focusing attention on the fact that the health impacts of sanitation and wastewater management are a product of both hazard and exposure. The 2006 Guidelines for the Safe Use of Wastewater, Excreta and Graywater (WHO, 2006) provide a framework for this analysis but have been widely reported to be complex and difficult to apply. SSP is a city-level tool based on this risk-assessment approach, which provides a more simplified framework that can be used to identify and assess health hazards and exposure pathways in a city (WHO, 2016). Where the application of SSP is challenging, an even simpler starting point is provided by the Shit Flow Diagram (SFD), a simple graphical representation and assessment of the fate of excreta in urban areas across the sanitation service chain (Peal et al., 2014). The SFD highlights the relative scale of flows from all relevant sanitation systems, and it identifies those which are broadly 'safely managed' and those which are broadly 'unsafe.' The SFD distinguishes between hazards that remain in the neighborhood and those that reach citywide drainage or are discharged downstream of treatment facilities. At a smaller scale, the Sanipath assessment tool provides much more detail on the relative importance of different exposure pathways in a neighborhood (Robb et al., 2017).

All these tools are based on risk assessment methodologies, and a further step is to draw on dose–response and infection–disease models. These are often brought together using quantitative microbial risk assessment (QMRA), which has been applied to determine the magnitude of risks to different population groups from contamination (Labite et al., 2010; Fuhrimann et al., 2017; WHO, 2019) and informed a conceptual approach developed to assess different sanitation options (Mills et al., 2018). The sanitation option generation model developed by Spuhler et al. (2018) includes public health as one of five criteria, although the assessment is limited to a scoring of technology compliance against effluent discharge standards. Further quantifiable methods for comparing and prioritizing sanitation improvements are needed that can address the risks caused by different failures along the service chain, to different user groups and at different scales.

The recent synthesis of sanitation and health-related research (Murphy, 2017; WHO, 2018) has highlighted several remaining knowledge gaps, particularly the absence of information relevant to conditions in LMICs. A key area for further research is the fate of pathogens in urban environments, particularly protozoa and helminths in sewers or drains (Murphy, 2017). Where onsite systems are prevalent, key research gaps include: the partitioning of different pathogen types in sludge and effluent; the effects of efforts to improve the performance of existing systems (e.g., regular emptying); and the potential for further pathogen reduction through additional onsite or decentralized secondary treatment processes. While modeling pathogen flows and improvement options can begin to inform options and priorities, there is also a need to balance complex analysis with simple decision trees or rules of thumb that can be more easily applied by decision-makers to ensure the highest-priority areas are given attention. Context-specific risk-based thinking is key, as promoted by the SSP approach, since population density, soil type, environmental conditions, stormwater hydraulics, groundwater contamination vulnerability and exposure pathways will inevitably differ from place to place. Without this approach, there can be no sound basis for comparing sanitation options in terms of their potential to meet public health risk objectives.

CLIMATE CHANGE

Climate change is a critical issue of our time and stands to severely impact sanitation systems both directly and indirectly. One way it may do so is by exacerbating the risks of fecal contamination and disease spread discussed above. The gravity of the situation has only recently been recognized, and it is timely to consider how climate change could and should be incorporated into sanitation decision-making frameworks to improve resilience (World Bank, 2011; ISF-UTS and SNV, 2019; WHO, 2019). When adopting a citywide, inclusive perspective, the issue becomes even more relevant, since the worst impacts are likely to fall upon vulnerable and marginalized groups (OHCHR, 2010). Climate change demands that we ask how technologies and service arrangements at various scales could be expected to perform under different climate-related scenarios, such as increased flooding or drought, such that this can be considered in decision-making processes. Equally, it represents an imperative to consider the mitigation potential of different options when selecting optimal solutions.

If global warming continues at current rates, it is predicted that climate change will substantially increase the frequency and magnitude of extreme flooding and drought in many regions, cause sea-level rise that will critically impact infrastructure in low-lying coasts, and drive increased variability in precipitation (Pendergrass et al., 2017; Hoegh-Guldberg et al., 2018). While the magnitude and complexity of the threats posed by climate change are increasingly well understood and documented, relatively little attention has been given to how these threats will impact drinking water and sanitation services and their management, despite their importance to human health (Howard et al., 2016). In this section we highlight key impacts of climate change on sanitation and disease spread, and current predictions about the performance of different solutions. It provides insights that can help ensure climate resilience becomes an integral consideration in decision-making about sanitation.

The impacts of climate change on sanitation are expected to be at least as significant as those on water supply, and in some circumstances, they may be even greater (Howard et al., 2016). The most frequently reported hazard to sanitation systems is high-intensity rainfall, causing flooding of onsite systems such as pit latrines and septic tanks, which poses serious public health risks (Braks and De Roda, 2013; Cann et al., 2013; Howard et al., 2016; Bornemann et al., 2019). Flooding of pit latrines, due to rising groundwater or the inundation of surface water, renders them inoperable and may readily disperse excreta into the groundwater or surface flood waters, creating a severe risk in areas where they are present in high numbers (UN-Habitat, 2008; Charles et al., 2009) or for low-lying or densely populated areas (UN Water, 2019). In the United States, England, and Wales, cryptosporidium outbreaks have been associated with flood events (Hunter, 2003) and a systematic review shows vibrio cholera as the most common pathogen implicated in extreme water-related weather events (Cann et al., 2013). While raising latrines is a commonly proposed adaptation solution, it needs to be considered in the context of the population that will be using the facilities, as some adaptions may cause the latrines to become inaccessible for the elderly, children and people with disabilities (Charles et al., 2009). Various studies have indicated an additional hazard from flooding of on-site systems when residents take advantage of floodwater to flush out their latrine contents (Chaggu et al., 2002, as cited in Charles et al., 2009; Williams and Overbo, 2015). In contrast, the effects of flooding on container-based systems (CBS) could be expected to be minimal because they do not leak into the environment (World Bank, 2019). However, CBS faces similar risks to onsite systems if access for emptying or treatment is affected.

High intensity rainfall also affects centralized sanitation systems, including potential damage to wastewater treatment plants (Howard et al., 2016), destruction or interruption of sewer mains and pump stations (Moyer, 2007) or sewer overflows (Major et al., 2011). In many cities, combined sewerage systems are used instead of separate sewers due to lower capital costs, particularly where the existing drainage network is used. However, in areas where there is expected to be an increasing risk of wet weather, the high risk of pathogen exposure from combined sewer overflows means they should be considered as an incremental control measure only, and must be combined with other measures to prevent exposure during or following rain events (e.g., public awareness of overflows and temporary closure of contaminated bathing sites) (WHO, 2018).

Drought and water scarcity have different impacts on each sanitation system type. In fact, it is the risk of drought and water scarcity that identifies centralized sewer systems, and to a lesser extent septic tanks, as the most vulnerable types of sanitation (Charles et al., 2009; Howard et al., 2010; Sherpa et al., 2014; Luh et al., 2017; Fleming et al., 2019). This is because drought and water scarcity can reduce the usability of water-based sanitation and cause sewers to block (Howard et al., 2010). During periods of water scarcity in a peri-urban community in Botswana, residents with toilets connected to a sewer reverted to using old pit latrines, or built new ones, putting water supplies further at risk due to contamination (McGill et al., 2019). Other studies have found composting toilets and pit latrines are the most resilient to climate change, as they do not rely on water supply

(Sherpa et al., 2014; Luh et al., 2017) or because adaptations are feasible (Howard et al., 2010). Septic tanks are considered more reliable than sewers, as the risk of clogging during water scarcity is lower due to the shorter pipe distance, with decentralized or solid-free sewers also found to be more resilient than centralized sewerage (Sherpa et al., 2014).

Whilst less commonly reported in the literature, sea level rise can have direct impacts on sanitation systems. Sea level rise and surges present a risk to the sewer outfalls that are common in coastal areas, as wastewater can back up and flood through manholes in roads and the toilets and washbasins of homes and buildings (PAHO, 1998; CEHI, 2003). Saltwater intrusion to sewers or wastewater treatment plants may also affect biological treatment processes (WHO, 2019).

More generally, climate change is expected to affect the fate and mobility of pathogens (Charles et al., 2009). As a result, climate change is likely to exacerbate existing health problems, including those related to poor sanitation (IPCC, 2014) and the spread of water-borne diseases (UN Water, 2019). Rising temperatures are also expected to increase the incidence of diarrheal disease (Hutton and Chase, 2016*)*. Climate factors determine the number, type, virulence and infectivity of pathogens transmitted through water or vectors that breed in water, and thus they may impact the associated infectious diseases (Vo et al., 2014). Increased precipitation intensity will create peak concentrations of pathogens in waterways due to sewage overflow and runoff (Vo et al., 2014). Increased groundwater flows and levels due to more rainfall and frequent or larger floods promote the spread of pathogens through greater mobility and survival, and greater saturation of soil increases pathogen survival (Charles et al., 2009).

In efforts to satisfy environmental objectives for sanitation, mitigation is also an important consideration. Human excreta is a source of greenhouse gas (GHG) emissions, and pit latrines have been estimated to account for approximately 1% of anthropogenic methane emissions globally (Reid et al., 2014). Biological processes in wastewater treatment plants are also believed to be significant GHG contributors in some countries (Mannina et al., 2016) and septic tanks are considered to be major contributors (González et al., 2018; Somlai et al., 2019). Composting toilets and regular emptying of septic tanks are proposed to reduce GHG emissions (Reid et al., 2014, IPCC, 2006), as are options that limit energy use in sewage conveyance. Examples include gravity-based systems and decentralized systems that reduce pumping distances as compared with centralized solutions (Carrard and Willetts, 2017) and blended gray-green-blue[1] infrastructure (UN Water, 2019). Further research is needed to develop a more nuanced understanding of GHG emissions from different types of onsite systems under common usage across LMICs.

So what does this mean for decision-making and options assessment? Global comparative studies on the performance of each technology under varied climate change scenarios, and evidence on emissions, need to be carefully applied in context-specific decision-making processes, taking into account the local climate, and technical and environmental factors. Risk-based approaches, as discussed above under 'Contamination,' remain applicable. However, they must be complemented by new thinking in relation to addressing uncertainty.

Climate change creates uncertainty due to our limited understanding of how climate hazards will change in specific locations, how climate change interacts with other forces (e.g., urbanization and land-use change), and how society will respond (Dessai and Hulme, 2004). In addition, the social systems connected to service use and management, and the interactions between social and bio-physical systems, need to be considered (Kohlitz et al., 2019). Often, technical and management systems for urban sanitation are poorly equipped to handle uncertainty and changing conditions. Addressing both dry and wet extremes calls for solutions at different scales ranging from the household level up to the city level (UN Water, 2019). A study on adaptability by Luh et al. (2017) found that no sanitation system performed well in all hazards, suggesting that the resilience of sanitation technologies is highly dependent on which climate-related hazards are considered. Despite uncertainties about the specific future impacts of climate change, cities can make informed decisions about how to increase resilience and adapt based on the best available information (Dessler and Parson, 2010). The field of climate adaptation commonly promotes nature-based systems and blended gray-green-blue infrastructure, which are suggested to be more cost effective, less vulnerable to climate change, offer mitigation co-benefits and provide better service and protection over its lifetime (UN Water, 2019). 'Low regrets' approaches to sanitation development – approaches that are beneficial regardless of the climate scenario – should also be pursued (Oates et al., 2014). Examples include: the scheduled emptying of latrines in advance of flood seasons, low water-use toilets and improved construction quality to reduce the infiltration of water into septic tanks or sewers.

Incorporating principles of adaptivity and flexibility into infrastructure and service arrangements is expected to assist managing sanitation systems in the context of uncertainty. Several water and sanitation professionals have argued that as an adaptation strategy, the diversification of facilities is preferable to focusing on just one type of facility or a centralized system, as a mix of facilities can increase resilience and diversify risk (Charles et al., 2009; ISF-UTS and SNV, 2019). Being able to change the management and operation of sanitation services and ensuring operators have a good understanding of sanitation system components increases the adaptability of services to changing conditions (WHO, 2019). Adaptive management improves responsiveness to different conditions by promoting continued learning through experimentation, feedback and innovation. Adaptive management measures could include preventative maintenance, involving operators in design and decision-making, and increased system monitoring connected to response or warning mechanisms (ISF-UTS and SNV, 2019).

In the context of supporting inclusive citywide sanitation decisions, attention must be given to vulnerable populations. Climate change does not affect everyone equally, and low-income

[1]Gray infrastructure refers to entirely human-built 'hard' systems such as pipes, levies and concrete dams. Green and blue infrastructure includes natural elements such as a floodplains or coastal forest but can also be engineered by humans (UN Water, 2019).

households are more likely to be in areas affected by sewage and septage overflow during floods (Hawkins et al., 2013). Low-income households are also more likely to use precarious sanitation systems that are easily destroyed or disrupted by climate hazards, and they typically possess the least capacity to cope with and adapt to shocks (Grasham et al., 2019). Urban sanitation decisions must take account of the differential impacts of climate change across social groups and their capacity to respond to those impacts. Climate risk assessments, the mapping of areas exposed to climate-related hazards, and social vulnerability indexes can be used to measure the vulnerability of populations, and overlaid with maps of flood, water scarcity or landslide hazards to identify areas where sanitation services could be disrupted (WHO, 2019).

It is critical that resilience and mitigation efforts be mainstreamed into current decision-making, rather than seen as an additional concern, given the long-term implications of today's development decisions and the need to avoid even greater costs in the future (World Bank, 2011). Acknowledging the uncertainty of climate predictions, and recognizing that in many cities sanitation systems will be affected by varied climate impacts, options should be selected that minimize regret (Oates et al., 2014; Hallegatte et al., 2019). When bridging the gap between climate science and infrastructure planning, addressing the complexity and uncertainty of climate impacts could result in paralysis in planning. Bornemann et al. (2019) suggests the need for better communication and explicit training designed to provide the next generation of key decision makers with additional appropriate analytical and problem-solving skills. Stress testing options under a range of plausible climate conditions relevant to the local context may assist in the management of uncertainty, and may help decision-makers to debate trade-offs between robustness, cost, safety margins, flexibility and regret (Hallegatte et al., 2019). More broadly, considering climate adaptation and mitigation also means that planning and policies need to incorporate and address the interconnections between climate, water resources, sanitation and water infrastructure, rather than consider these issues separately (McGill et al., 2019).

COST

Achieving citywide inclusive sanitation requires investment in infrastructure that meets the needs of all urban areas, including low-income settlements. It is widely recognized that ensuring the provision of citywide sanitation services involves high capital and operational costs. Cities need to consider how to provide universal access to safe sanitation through suites of technologies and operating configurations that incur the lowest cost to society as a whole. This requires addressing long-term financial liabilities, rather than short-run investments or budgeting constraints, and it therefore requires an understanding of the full life-cycle costs and relevant externalities of different sanitation options (Mitchell et al., 2007). However, there are is a paucity of data on the relative costs of different options for providing sanitation services in urban areas, as analyses are generally confined to capital cost comparisons rather than life-cycle costs (Daudey, 2018). Consequently, there is a shortage of data to inform decision-making about possible service scenarios to achieve citywide sanitation.

While several recent studies have provided critical financial perspectives for urban sanitation, they have focused on discrete aspects of the issue. These include: studies of willingness to pay (for example, Vásquez and Alicea-Planas, 2018; Acey et al., 2019; Tidwell et al., 2019); the business case and cost recovery for fecal sludge management (e.g., Andersson et al., 2017; Blackett and Hawkins, 2017; Otoo and Drechsel, 2018); and analysis of the pro-poor reach of infrastructure investments (Hutchings et al., 2018). Analyses comparing sewer and onsite technologies exist (Dodane et al., 2012; McConville et al., 2019) but can be limited by inconsistent analytical boundaries due to the exclusion of costs borne by households (for example Stantec, 2019). These types of analyses do not address the fundamental need for cost comparisons and decisions across different scales, technologies and service options. Such comparisons are needed to broaden the suite of options considered beyond the dominant investment focus on large-scale wastewater treatment and sewerage systems (Hutchings et al., 2018) that typically serve better-off socio-economic groups (McGranahan, 2015). This section outlines the evidence base to date, and points to important areas which need to be included in the robust consideration of costs in citywide sanitation decision-making.

A recent review (Daudey, 2018) confirmed that available contextualized data on the costs of urban sanitation solutions is surprisingly limited and of variable quality. However, the body of literature does identify some typical cost characteristics for urban sanitation systems. In general, "lower tech" (typically onsite or simplified sewer) solutions are considered less costly than "higher tech" (conventional centralized) systems. However, the systems under consideration typically do not offer equivalent levels of service or treatment (Daudey, 2018; Rozenberg and Fay, 2019) and as such are not directly comparable. This is of concern given the above sections discussing contamination and public health risks, including the exacerbation of these with climate change. In addition, across the lifecycle of sanitation infrastructure, the expenditure required for operation and maintenance (compared with capital expenditure) is highly variable. Daudey (2018) found that operations and maintenance expenditure ranged from 6% to more than 60% of total expenditure, with a lower proportion in the case of centralized sewerage systems (given their high capital costs) and a higher share for FSM-based systems (Dodane et al., 2012; Daudey, 2018; Stantec, 2019). However, such comparisons are not useful for informing investment decisions, since they do not provide a basis of comparison between options with a consistent metric. In addition, the costs of sanitation systems are highly contextual, with determinants related to technical, topographic, demographic, socio-economic and material factors (Daudey, 2018). For example, when modeling the costs of onsite and offsite options for the delivery of sanitation in Soweto, South Africa, Manga et al. (2019) found that population density and rates of connection to sewers had a significant impact on the relative costs of systems, with sewers becoming attractive from a cost point of view once population densities exceed a threshold value that varies depending on the extent of pumping and treatment options.

The challenges associated with defining typical cost characteristics of sanitation options are compounded by limitations in the available evidence. Daudey (2018) identified three main limitations in the literature on urban sanitation costs: inconsistent inclusion of life-cycle costs; failure to include costs for the whole service chain; and a lack of transparent reporting on the costing methodology. Few analyses transparently include life-cycle costs, with many focusing on only one or two cost types or neglecting to disclose which costs are included. Only six of the 50 studies reviewed in Daudey's (2018) analysis included at least capital, recurrent and capital maintenance costs. The review itself also excluded expenditure on direct and indirect support, two cost components identified in the WASHCost costing approach (Fonseca et al., 2011) that are critical for the sector to move toward professionalized management arrangements for service provision. Exploring the costs associated with direct and indirect support activities would be a valuable contribution from future cost analyses seeking to inform citywide inclusive sanitation. Analyzing these costs requires an assessment of the costs associated with economic and environmental regulation, inter-sectoral coordination, monitoring and IT systems (Fonseca et al., 2011). Full life-cycle costing in cost-effectiveness analyses must also acknowledge the different expected life spans of infrastructure alternatives in order to compare options on an equal footing. Such comparisons need to take into account anticipated phasing of investment and differences in asset capital and operating cost profiles over time (Mitchell et al., 2007).

The second limitation Daudey (2018) found in the literature was that many studies fail to include costs across the whole sanitation chain (containment, emptying and transfer, treatment, reuse/disposal), with fewer than half the reviewed studies (19 of 50) addressing at least containment, emptying and transfer. Studies which focus only on parts of the service chain risk misrepresenting the true costs of services, limiting their usefulness in investment decision-making for citywide services. Potential benefits or revenue streams can also be missed if the full chain is not included (Willetts et al., 2010; Andersson et al., 2016; Lazurko, 2019; Trimmer et al., 2019). It is also necessary to consider the potential increased demand for some resources such as nutrients for fertilizers, with scarcity increasing chemical fertilizer prices and demand for alternatives such as treated sludge expected to increase, attracting investment (Hutton and Chase, 2016).

The third limitation identified by Daudey (2018) was that reporting of cost analyses was often opaque in terms of methodology and specification of the options considered. This limits the extent to which included data can be interpreted as relevant (or not) for planning in different contexts. This illustrates a sector-wide challenge that cost information is not commonly presented in a form suitable for informing decision-making (Hutton and Chase, 2016), and there is no widely accepted and agreed cost-effectiveness methodology. Another challenge for citywide service planning is that the costs of ensuring inclusive services for the hardest-to-reach populations are not well understood and are easily underestimated (Hutton and Varughese, 2016).

A critical consideration for improving our evidence base is comparing system costs for options that meet an equivalent, specific objective (Mitchell et al., 2007). In the case of sanitation, the specific objective is to choose a service level that protects public health and the environment and addresses the contamination issues discussed in the section 2 of this paper. Clarifying this objective is necessary to prevent the inappropriate direct comparison of options with different service levels, such as comparing onsite systems without secondary treatment to sewered systems. To achieve a similar level of service, the costs of reducing the hazard or exposure associated with onsite systems (for example through secondary treatment) should be included in order to provide a more appropriate assessment of relative costs (Mitchell et al., 2016). Similarly, costing any system, whether it is an offsite, onsite or container-based system, without costing the relevant required management, for instance the costs of regular desludging or maintenance, is also misleading, since the required service level cannot be maintained without incurring these costs. To support defensible cost comparisons on a level playing field, options should be required to reach a minimum tolerable level of public health risk. This will require an approach to risk assessment that can inform costing analyses.

The costs of climate change adaptation measures to ensure a minimum ongoing service level and tolerable contamination risk should also be considered. Predictions are needed for expected performance in different climate scenarios, such that maintenance and repair costs for adaptation and response can be integrated into the cost analysis (World Bank, 2011). This is likely to be challenging, given the uncertainties associated with climate change, but also cannot be ignored. The various climate hazards associated with urban sanitation discussed above will increase maintenance costs, as repairs and replacement expenses are expected to become more significant and frequent. Floods are among the most costly types of disaster, especially as they increase in frequency and severity (Cissé, 2012 in Sherpa et al., 2014). The costs of adaptation measures should therefore also be considered. Examples of adaptation measures include increasing the resilience of infrastructure by providing additional flood protection for latrines or treatment plants, increasing the capacity of sewers, and sealing pit latrines. Equally, decisions about whether to prioritize more robust or easily rebuilt low-cost infrastructure must be made. For example, the Char communities in Bangladesh, who have a history of exposure to rainfall variability and adapting their lifestyle (e.g., through migration) build more temporary low-cost structures that can be rebuilt rather than expensive permanent structures that would regularly be abandoned (Charles et al., 2009).

Climate change will also increase operational costs, particularly for centralized sewerage systems. This is due to the increased cost of energy as well as the pumping and treatment costs associated with increased volumes of wastewater and stormwater due to precipitation increases (Major et al., 2011). In addition to the costs of repairing and replacing damaged infrastructure as sea levels rise, cities may no longer be able to rely on gravity to discharge combined sewer overflow and wastewater effluent, and this will increase pumping costs (World Bank, 2018). Adaptive management can increase operational costs, for example due to increased human resources and training costs, asset management systems, and monitoring and warning systems. While these are necessary in non-climate change conditions, addressing the specifics of climate change adds another layer of complexity to evaluation and decision-making processes for city planning that is already challenged by incomplete information about the range of future costs (World Bank, 2011).

As a way forward to inform decision-making, cost-effectiveness comparisons should ensure system-wide, consistent boundaries of analysis such that different infrastructure configurations, considering the whole service chain, can be appropriately compared. This requires taking a whole-of-society perspective which considers all costs over time and identifies which options represent the least cost to society to achieve the specified service level (Mitchell et al., 2007; Willetts et al., 2010). Including all cost perspectives (e.g., user, operator, initial investor) is particularly critical when comparing options with substantially different cost profiles in terms of their distribution and timing (Mitchell et al., 2007).

Once a sanitation option is decided upon that incurs the least cost to society, decision-makers can then develop mechanisms for financing the selected option and determine an appropriate distribution of costs across different stakeholders to ensure affordability for low-income households (Mitchell et al., 2007). Transfer payments may be required, for example an appropriate household payment to a service provider, or a subsidy from a municipality to a service provider. This is critical when considering equity in citywide sanitation, particularly as low-income areas may require higher cost solutions due to their hard-to-reach locations or higher-cost-to-user solutions such as onsite systems. Decision-makers could also change the way costs are distributed, as households who pay for FSM-based onsite systems and emptying services typically incur a greater portion of costs than those with centralized systems for which a larger share of costs is borne by utilities and other service providers (Daudey, 2018; Dodane et al., 2012). With the complexity of the sanitation chain and its multiple actors and institutions, it remains a significant challenge to conduct robust costing analyses at the 'system' level. However, without this, there is potential for chosen service systems to burden governments and society with expensive solutions, or to inadvertently disadvantage the poorest and most vulnerable, for instance by only costing and examining one part of the sanitation chain in isolation.

IMPLICATIONS

While the interlinkages between contamination, climate change and costs for sanitation options and investment decisions were noted at the end of each section, there are three key cross-cutting challenges which are important to draw out.

Firstly, the burden of contamination, climate change and costs associated with sanitation is unequal. To date, reducing inequalities has mostly focused on access to services. However, inequalities in exposure to fecal contamination, particularly in the face of climate change (notably flooding) also warrant attention and are under consideration in the evolution of monitoring of SDG 6.2. The cost burden of living with elevated risk of contamination and climate change effects such as flooding falls disproportionately on the poor. To date there has been limited work on how costs of building resilience should be equitably shared.

Second, inadequate data and evidence gaps limit informed decision making across each of these three areas. Research on the fate of different types of pathogens in dense urban living environments is urgently needed to address contamination (Amin et al., 2020; Foster et al., 2020). For climate change we require cohesive ways to bring together disparate climate science, engineering, public health and social science knowledge. As noted earlier, accumulation and analysis of cost data across different sanitation options for the full sanitation service chain is only recently emerging.

Third, whilst this paper primarily tackles the technical inputs needed for improved decision making, in reality we recognize the significant role of politics and power dynamics in real-life decision-making. That is, sanitation investment decisions rarely follow a rational planning process, as there are many additional factors that intervene, such as politics, ideologies, implicit beliefs and assumptions, restrictive policies or standards, and insufficient confidence to deviate from traditional approaches (Abeysuriya et al., 2019). The top-down influence from politicians, funding agencies or other investors may also shift focus to capital and/or large investments rather than the ongoing expenses or consideration of progressive improvements that are important for sustainability.

This said, a risk-based approach to decision making will remain important to identify and target interventions which address inequalities; such an approach is vital to ensure that incremental investments are selected based on their comparative cost effectiveness in terms of their broader benefit to society. A stronger understanding of pathogen flows and climate hazards is essential to enable decision makers to determine the highest priority risks and the real costs of their mitigation. Attention to these risks can also inform appropriate sequencing and prioritization of investment, and the effective delivery of incremental improvements. An incremental approach promotes a gradual build-up of capacity and allows feedback and incorporation of new information, which is particularly important in the context of climate change and rapid city level development. A key ingredient is therefore increased monitoring to understand the operation of sanitation systems, including from a financial perspective, as well as real time data to identify and manage risks. Critical for sustainability across all areas is an increased priority on operation and maintenance, without which the benefit of any investment will be effectively lost with consequent further downward pressures on both equity and resilience in the city.

Putting these approaches and research into practice requires new capacities to be built. Optimizing urban sanitation investment decisions is a complex challenge, and it requires high levels of expertise and technical know-how at the city level. The skills required go well beyond the 'technical' engineering focus that has tended to dominate historically. Many of these skills may exist but are rarely brought together to facilitate a multi-dimensional planning process that balances positive health outcomes, sustainable services and cost effectiveness.

CONCLUSION

Contamination, climate change and costs are three aspects of sanitation that require critical attention in decision-making to ensure that sanitation solutions are chosen that achieve the public health, sustainability and economic objectives integral to inclusive citywide sanitation. Bringing a contamination and climate adaptation and mitigation focus to decision-making requires risk-based thinking and will emphasize the importance of addressing inequalities and prioritizing vulnerable communities, not just for equity but for citywide public health. Operation and maintenance are cross cutting challenges that must be considered upfront when investigating sanitation options, particularly how these options are to be resourced and financed. Analysis of cost effectiveness against consistent service objectives will permit improved comparison of the mix of sanitation options likely to be appropriate to different contexts across a city. This will create an opportunity to then separately consider how costs may be fairly distributed across different actors. Research and data gaps need to be addressed, particularly in relation to fecal contamination risks and climate change, and particularly as relevant for the conditions found in dense low-income areas. With the large investment needed to achieve citywide sanitation for all, consideration of the three areas of cost, climate and contamination can enhance recognition of sanitation's importance for a sustainable healthy city and important contribution to health, sustainability and economic outcomes.

AUTHOR CONTRIBUTIONS

JW, NC, JK, and FM conceived the objective of the manuscript and conducted background research. FM and JW refined framing and structure. FM took the lead in drafting the manuscript with contributions by JW (all sections), BE (contamination, abstract, introduction, and conclusion), NC (costing), and JK (climate). FM addressed reviewers' comments. All authors reviewed the final version.

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2.4 Updates and summary

The history of sanitation drivers at the start of this chapter demonstrates a shift from public health as the primary motivation for investments. This transition was influenced by significant public health improvements in HICs. As detailed in Paper 1, while public health remains an assumed or desired objective for sanitation investments, mainstream approaches to planning and design often neglect health impacts. This oversight stems from evidence gaps regarding pathogen reduction or releases from different sanitation technologies, especially those used in the context of LICs. Additionally, decision-makers lack adequate tools to assess how sanitation systems and their failures affect health across various transmission pathways and how to prioritise investments to progressively reduce these risks. Although climate and cost are critical drivers for sustainable sanitation, this thesis focuses on the public health driver as a fundamental requirement for sanitation improvements. Since the paper's publication in 2020, there have been several advances in research related to health, climate and cost. This section summarises the updates related to public health risks and sanitation.

There has been some increase in recognition of the need to consider health impacts across the sanitation service chain, including improved monitoring of viruses in wastewater and promoting the One Health approach. The importance of addressing risks beyond basic access was recognised in the most recent burden of disease study, which assessed the impact of sewer connections and safely managed water supply on health outcomes (Wolf et al., 2023). However, due to a paucity of exposure-response data, other aspects of safely managed sanitation, such as on-site sanitation, could not be evaluated. While the recent randomised controlled trials (RCTs) were conducted before 2020, recent articles have reflected on the implications and explanation of the limited reductions in diarrhoeal disease from increased toilet access and are discussed further in Section 3.2 below. Additionally, since 2020, there has been increased monitoring and reporting of recreational water quality and sewer overflows in high-income countries, such as England and France, drawing public attention to faecal contamination of waterways. Wastewater surveillance also gained prominence during COVID-19, with many countries now equipped for ongoing monitoring of viruses or other wastewater contaminants (Hamilton et al., 2024). The broader WASH sector has also increased attention on antimicrobial resistance, the One Health approach integrating human, animal and ecosystem health, and WASH in healthcare facilities. While these may not directly inform sanitation infrastructure decisions, they raise awareness about the health implications of sanitation practices.

There has been a significant increase in attention and research regarding the importance of climate change in sanitation investment decisions, raising awareness of the health risks associated with climate hazards, particularly heavy rainfall. Recent research has examined the impacts of climate change on sanitation (Hyde-Smith et al., 2022; Lebu et al., 2024; UTS-ISF et al., 2021), methane emissions from sanitation (Doorn et al., 2000; Johnson et al., 2022), and climate finance for sanitation (Dickin et al., 2020; IRC, 2023). These studies have heightened awareness of health risks linked to flooding and washout of pathogens from drains or OSS, with climate risks now incorporated into the WHO guidelines on water safety planning (Okaali et al., 2019; WHO, 2019). The adoption of a target for climate-resilient water and sanitation in the global goal on adaptation (UNFCC, 2024) signals a likely increase in monitoring climate impacts and resilience. While the focus on climate has the opportunity to bring attention to health risks from poorly managed sanitation, there remains a concern that funding aimed at meeting emissions targets may overshadow health drivers.

Health considerations remain underrepresented in discussions on sanitation costing. Recent costing tools and research on equity, life cycle and consideration of the entire service chain could enable increased consideration of health outcomes of investments. Recently, several costing tools and databases have been developed (Sainati et al., 2020; World Bank Group, 2021), with some, such as the 'EquiServe' platform, assessing service delivery costs and coverage for vulnerable populations (www.equiserve.io). Various studies emphasise the importance of accounting for the full sanitation service chain costs, including ongoing costs (Carrard et al., 2021; Manga et al., 2020). Although these do not specify differentiated public health outcomes, they highlight the need to ensure ongoing service operation across the chain. These studies highlight the challenges of applying cost data across different contexts due to variations in sanitation technologies, service delivery methods and geographical factors. At the intersection of climate and finance, debate continues on access to climate finance for sanitation adaptation or emissions reductions, with new guidance launched at COP29 on climate investment in sanitation (Global Climate Fund, 2024). While the extent of climate finance for sanitation remains uncertain, it is expected to influence future decision-making.

From the review and clear shift away from health drivers for sanitation decisions in recent years, I focused my research on addressing evidence gaps related to the public health risks of OSSs and how evidence can be generated to understand risks and inform decisions. This focus will be further discussed and justified in the following chapter.

3. Health risks of on-site sanitation

- Public health risks of sanitation
- On-site sanitation focus
- Monitoring health risks of OSS

3.1 Introduction

Building on the review of drivers and the shift away from a focus on the public health objective of sanitation investments, this chapter reviews the literature on sanitation-related health risks in LMICs and outlines the ‘public health engineering’ approach to sanitation adopted in this thesis. Given that OSSs are the primary type of sanitation in LMICs, I review the evidence of the increasing use and promotion of OSSs and summarise the health risks of varied OSS failures related to faecal pathogen releases and exposure. Lastly, I present literature on the health and engineering approaches to assessing and monitoring health risks of sanitation, concluding with a summary of the key research gaps.

3.2 Focus on public health

The public health driver is the focus of this thesis, and this section presents the ongoing public health issues associated with sanitation, particularly in LMICs, and summarises the challenges in quantifying the health impacts of different sanitation solutions and their management. I then present a public health engineering approach to sanitation and the value of this perspective in integrating health and engineering aspects into research and planning.

3.2.1 The challenges of quantifying public health impacts of sanitation

Diseases related to faecal pathogens remain a critical challenge in many LMICs, with poor sanitation contributing to significant environmental contamination. While sanitation improvements are presumed to benefit health, particularly in reducing diarrhoeal disease, proving these outcomes has been challenging due to complex relationships between exposure and health, and methodological issues. This section summarises evidence on faecal-related diseases in LMICs, the difficulties in assessing health outcomes of sanitation interventions, and their implications for understanding and researching health risks and sanitation systems.

Despite progress in sanitation globally, faecal-related diseases such as cholera, typhoid, and helminth infections, and vector-related diseases such as trachoma, remain significant public health concerns, especially for LICs (WHO, 2018). Children are disproportionately affected, with long-term consequences of exposure to pathogens such as chronic undernutrition and stunting (Troeger et al., 2018). Over 1 million deaths from diarrhoea in 2019 were attributed to unsafe WASH, with greater proportions of diarrhoea-related diseases attributed to WASH in LMICs (66%–76% of diseases prevented through safe WASH) compared to HICs (18%) (Wolf et al., 2023). Approximately 40% of diarrhoeal deaths in 2016 were attributable to inadequate sanitation (Prüss-Ustün et al., 2019), highlighting the critical need for sanitation improvements to prioritise public health objectives (WHO, 2018).

While several studies have found that inadequate sanitation contributes to health impacts, some studies have found improving sanitation had little to no positive health outcomes. Systematic reviews have shown sanitation's positive impact on health outcomes, such as reducing diarrhoea risk by 24% (Freeman et al., 2017; Hunter & Prüss-Ustün, 2016; Wolf et al., 2018, p. 201, 2022). In contrast, health trials and other reviews that tested the effectiveness of sanitation interventions on health outcomes found weak or no positive benefit (Contreras & Eisenberg, 2019; Cumming et al., 2019). Randomised control trials (RCTs) in Bangladesh, India, Mozambique and Zimbabwe reported little or no reduction in diarrhoea or improvements in child growth from improved latrines (Clasen et al., 2014; Cumming et al., 2019; SHINE et al., 2015). Reviews of the impact of sanitation on indicators of faecal exposure along principal transmission pathways and on microbial source tracking markers found minimal effects of sanitation interventions (Mertens et al., 2023; Sclar et al., 2016). These findings do not negate sanitation's role in health improvements but highlight the complexity of relationships and challenges in isolating sanitation's impact (Contreras & Eisenberg, 2019; Whittington et al., 2020).

Below is a summary of four key challenges that complicate the assessment of health outcomes linked to sanitation improvements:

- **Multiple pathways for pathogens transmission:** As illustrated in the F-diagram (Figure 3.1), faecal contamination can occur through numerous pathways aside from sanitation, including animal faecal sources, child open defecation, food and water supplies, or other background environmental contamination (Ercumen et al., 2018). Combining WASH interventions may make it difficult to isolate the health outcomes of sanitation alone (Freeman et al., 2017; Hyun et al., 2019), while *E. coli* and other pathogens in the environment can also come from animal sources (Mertens et al., 2023).

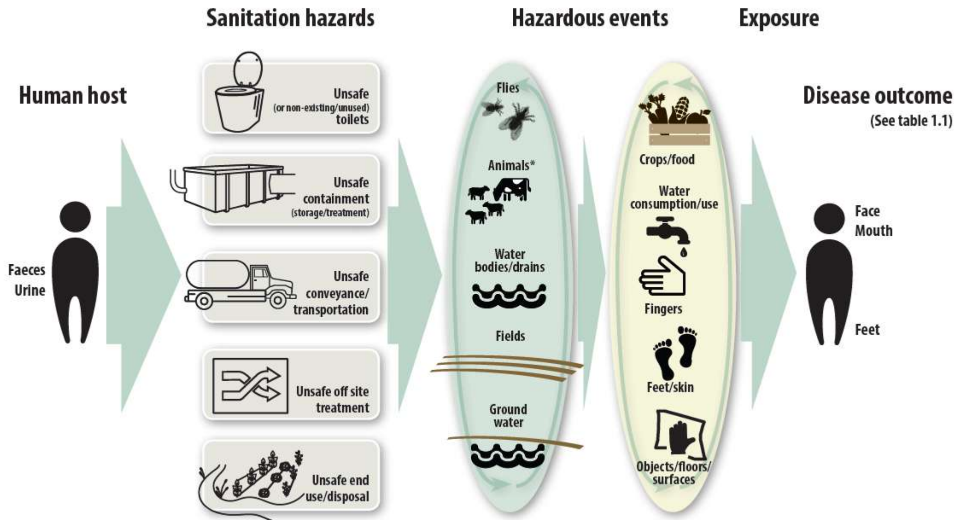


Figure 3.1 *F-diagram demonstrating pathways of transmission of faecal pathogens (WHO, 2018)*

- **Community coverage thresholds:** Health benefits depend on achieving high sanitation coverage within the community (Contreras et al., 2022; Wolf et al., 2019). Studies suggest that thresholds above 60%–75% are associated with reduced diarrhoea mortality, but defining and achieving sufficient coverage remains challenging and not always reported or achieved with studies on OSS interventions (Contreras et al., 2022).
- **Safe management of excreta:** The shift from increasing access to toilets under the Millenium Development Goals (MDG) to the SDG target of safe management of excreta across the service chain represents a critical advancement in consideration of health risks. Evaluating interventions based solely on access to improved toilets overlooks the critical issue of excreta containment, as many improved toilets fail to adequately contain human waste (Mertens et al., 2023). Studies comparing improved sanitation options have shown that sewer connections are associated with reduced risk of diarrhoea, even without fully accounting for the level of wastewater conveyance and treatment (Contreras & Eisenberg, 2019). Additionally, poor management of child faeces may be another source of contamination, further highlighting the limitations of assessing sanitation interventions based only on toilet access (Fuhrmeister et al., 2020).
- **Conditions are too varied to analyse collectively:** The wide variations in sanitation interventions and contexts make it difficult to generalise results (Contreras & Eisenberg, 2019; Goddard et al., 2020). Unlike health or water interventions, sanitation projects differ significantly in design, coverage, and operational approaches, which can limit combined analysis (Contreras et al., 2022; Freeman et al., 2017).

While the health benefits of sanitation improvements are evident in some contexts, studies reveal significant variability and complexity in outcomes. The effectiveness of interventions depends on factors such as community-wide coverage, safe excreta management, and addressing multiple contamination pathways. This thesis builds on these insights by addressing evidence gaps in health risks associated with excreta discharge across the sanitation chain, with a focus on OSSs in LMICs.

3.2.2 A public health engineering approach

As highlighted in the previous chapter, greater integration of public health considerations into sanitation investment decisions is needed. As demonstrated above, health studies often focus on the binary presence or absence of an intervention, such as access to a toilet, rather than examining the broader function and risks of sanitation systems. The somewhat narrow focus of sanitation as a health intervention leads to a binary view of sanitation rather than considering more critical engineering factors related to design, functionality, operation and performance. Integrating public health considerations into sanitation investment decisions requires moving beyond the binary question of providing access to toilets. Instead, decision-making must consider how the system functions in-situ, rather than ideally, including how excreta are managed across the entire sanitation service chain.

Building from the limitations identified in the recent health trials outlined above, it is evident that health studies need to evaluate how sanitation systems influence disease transmission pathways and contribute to environmental contamination. This demands a deeper understanding of how sanitation systems are designed to function, how they actually perform in practice, and how their function or failures introduce pathogens into the environment. While some studies have focused on critical exposure and environmental contamination pathways (i.e. the SaniPath approach), they often neglect to identify the source of contamination, such as the specific sanitation system failure. This gap hinders efforts to identify what specific sanitation improvements could contribute to reducing health risks.

To overcome these challenges, this research adopts a ‘public health engineering’ approach to improve how public health risks are considered in planning, design and assessment of sanitation systems. The following section provides an overview of this approach and its potential benefits.

What is public health engineering?

Public health engineering, also known as sanitary engineering, is the intersection of engineering and public health and focuses on engineering methods to modify the human environment with the objective of preventing or reducing disease transmission and improving the population's health (Cairncross & Feachem, 2018; Gelting et al., 2019). Public health engineering encompasses water, sanitation, solid waste and air quality with the aim of safeguarding public health (Witcher, 2020). It is centred on a multidisciplinary approach, combining the precision, innovation, and structural approaches of engineering with the nuanced, people-centred focus of public health (Cummings et al., 2024). It considers how the development or improvement of water, sanitation and waste systems can address environmental contamination and disease transmission from an understanding of local epidemiology and exposure patterns.

Public health engineering emerged in the early 20th century during the industrialisation period, often referred to as the 'Great Sanitary Awakening'. This period stemmed from the realisation that disease outbreaks were associated with contaminated wells and overloaded cesspools, which were addressed by engineering solutions, including flush toilets and sewers (Mihelcic et al., 2017). In emergency settings, the importance of public health engineering gained traction during the 1970s when doctors working for the International Committee of the Red Cross (ICRC) developed a model called 'the health pyramid' as shown in Figure 3.2. This model focused on a bottom-up approach to managing the health of vulnerable populations, starting with water and sanitation in the immediate environment, rather than a traditional top-down curative care approach (ICRC, 2013; ICRC & Eawag, 2017). Guidance on public health engineering in emergency settings suggests WASH should be considered as an integral part of medical programmes, in the same way as vaccinations, and requires consideration of technical, human behavioural and cultural aspects (MSF, 2010).

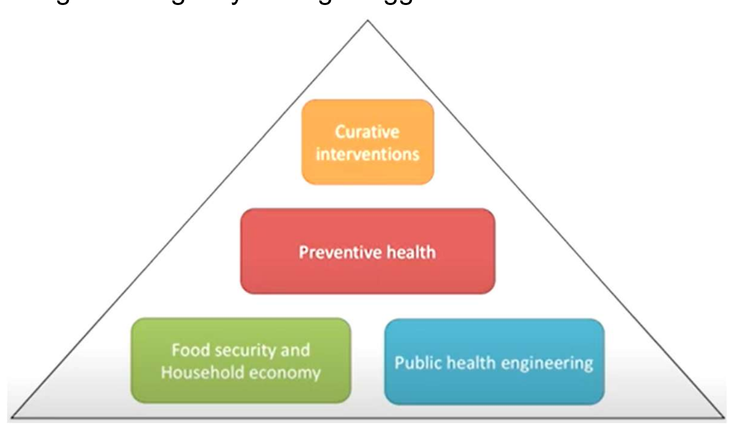


***Figure 3.2** Health Pyramid as part of a training module on public health engineering for emergency settings by Eawag and IRC*

Reinstating the public health engineering approach to sanitation

In recent decades, there has been a shift away from the practice and education of public health engineering. In the USA during the 1970s, the rise of environmentalism prompted the establishment of the Environmental Protection Agency (EPA), which took over governance of sanitation and wastewater (Gelting et al., 2019). Engineers working for the Public Health Service transitioned to the EPA or state environmental departments (Witcher, 2020). At the same time, civil and environmental engineering programs deprioritised public health training, further diminishing expertise in this area (Pakpour et al., 2022).

From a health sector perspective, sanitation is often perceived as a technical engineering task, with its health and economic implications underestimated or overlooked (Cummings et al., 2016). Public health professionals commonly focus on disease prevention through medical interventions, such as vaccinations, whereas an engineer's view of prevention leads to measures that can reduce environmental exposure, such as WASH improvements (Templeton, 2015). For example, in Zambia, the Public Health Act focused predominately on curative measures, and sanitation is typically only prioritised by the health sector during public health emergencies, such as cholera outbreaks (Kennedy-Walker et al., 2015). This difference in perspectives reflects on some of the interdisciplinary challenges of public health engineering. Public health professionals prioritise health outcomes and community impact, whereas engineers focus on the technical feasibility and efficiency of solutions (Cummings et al., 2024). Overcoming this gap will require improved communication and collaboration.

Historically, the World Bank's 1980s sanitation planning approach emphasised maximising health benefits as the primary objective when identifying sanitation interventions (Kennedy-Walker et al., 2014). Yet, as examined in Paper 1 and the review of sanitation drivers, there is little evidence that health is central to current sanitation investment planning in many LMICs (Cummings et al., 2016; Mills et al., 2020). Integrating public health metrics into engineering design could improve the efficiency and targeting of sanitation interventions. However, engineering design processes rarely consider exposure risks and epidemiological data, underestimating the public health consequences of engineering decisions (Cummings et al., 2024).

Several authors advocate for the reintroduction of public health engineering to address the ongoing challenges of sanitation and public health (Cummings et al., 2024; Gelting et al., 2019; Witcher, 2020). Cummings et al. (2024) call for a paradigm shift that prioritises public health in infrastructure planning and emphasises interdisciplinary collaboration between engineers and public health practitioners to tackle the complex public health challenges intertwined with the built environment. In *Back to the Future: Time for a Renaissance of Public Health Engineering*, Gelting et al. (2019) highlight historical successes from the USA, including integrating a division of the Sanitation Facilities Construction program into the Indian Health Service, which improved WASH outcomes in underserved areas. However, the disconnect between health and engineering sectors continues to hinder effective sanitation implementations that safeguard public health (Mihelcic et al., 2017; Witcher, 2020).

Although the public health engineering approach is valuable to sanitation research and investment, and I have applied it in my thesis, it has limitations, particularly how it is integrated into existing siloed health and infrastructure sectors. Health authorities have effectively led rural sanitation campaigns focused on behaviour change, such as the community-led total sanitation approach (Kar & Chambers, 2008), but often lack the resources or capacity to implement sanitation systems beyond the toilet (Cairncross et al., 2010). Addressing these challenges requires cross-disciplinary approaches, including integrating WASH into health policies, recognising WASH as a health priority in national planning, and regulating the health impacts of WASH beyond eliminating open defecation and water quality standards (Cairncross et al., 2010; WHO, 2018). Additionally, capacity building within engineering and infrastructure sectors is essential to incorporate public health considerations into planning and design processes, including reintroducing education on public health into engineering education (Oerther, 2018; Witcher, 2020). While these challenges are significant, they lie beyond the scope of this thesis.

Counter to the reinstating a public health engineering approach, several authors arguing for a shift to ‘environmental sanitation’ and ‘environmental engineering’ approaches, which emphasise the interactions between sanitation and the wider environment (Bartram & Setty, 2021; Budge et al., 2022; Mihelcic et al., 2017). Budge et al. (2022) argue that addressing multiple disease transmission pathways, including solid waste, drainage, animal excreta management and vector control, is needed to achieve transformative WASH outcomes. Mihelcic et al. (2017) propose that environmental engineering can be applied beyond the traditional environmental focus to address broader sustainable development objectives, including public health challenges. At the same time, Bartram and Setty (2021) propose an environmental health science and engineering approach to enhance evidence-based interventions. While these perspectives highlight the interconnections between sanitation and environmental systems, as discussed in the previous chapter, the shift away from health-centred designs and the lack of health data to inform decision-making is a concern. While I agree public health is included in the broader scope of "Environmental Sanitation" and that environmental protection and sustainable development are important objectives, I worry that this broader scope will continue prioritisation on more downstream risk mitigation investments, such as treatment plants and reuse. Whereas a "Public Health Engineering" approach encourages an assessment along the entire chain and will ensure focus is also upstream, at the containment and excreta releases near the household where human exposure is high. Investments based on a broader "Environmental sanitation" approach would find a treatment plant investment more favourable than the more complex sanitation improvements and stakeholder engagement needed to address containment risks. Therefore, I argue for reinstating a narrower public health engineering approach in LMICs where the health burden from faecal related diseases remains high, to refocus sanitation efforts on safeguarding public health, with environmental protection considered as a broader or second tier objective. This perspective underpins my thesis, which aims to demonstrate the critical role of sanitation in protecting health and that prioritising public health risks could increase attention on containment issues.

3.3 On-site sanitation focus

This section outlines the rationale for focusing on OSSs in this thesis. It highlights their increasing global use compared to sewer connections, examines their role as a sustainable solution within the Citywide Inclusive Sanitation (CWIS) approach, and reviews the health risks associated with OSSs along the service chain. Particular attention is given to gaps in evidence relevant to LMICs, with an emphasis on containment failures.

3.3.1 The role of OSSs in global sanitation services

OSS, including septic tanks and pit latrines, are used by more people globally than sewer connections (Figure 3.3). In 2022, over 3.6 billion people used OSSs, representing 63% of the population in rural areas and 33% of urban populations (UNICEF and WHO, 2023). In LMICs, OSSs are the primary form of improved sanitation for 70% of urban and 85% of rural populations. The global use of septic tanks has grown faster than sewer connections and improved latrines over the past two decades in both urban and rural areas (Figure 3.3). High rates of urbanisation have increased pressure on urban infrastructure development, and the development of wastewater and faecal sludge infrastructure is not keeping pace (UN-Habitat, 2023).

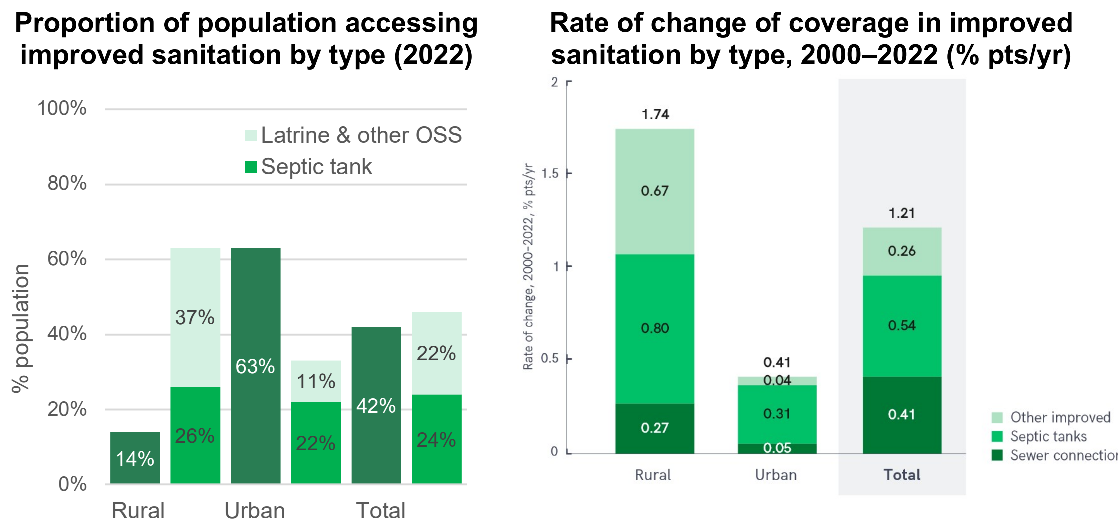


Figure 3.3 *Global SDG 6.2 data on type of sanitation (2022) and rate of change of coverage (2000–2022) (UNICEF and WHO, 2023)*

Historically, OSSs have been perceived as an inferior interim solution compared to centralised sewerage, especially in urban areas (Gambrill et al., 2020; Mitra et al., 2022; Paterson et al., 2007). This perception persists in some government and donor policies, with sewerage systems receiving 20 times greater investment by donors than for FSM services in urban areas, yet sewers fail to reach low-income areas (Hutchings et al., 2018). Centralised sewerage systems have mainly served small, often wealthier, areas of cities rather than low-income or challenging areas (McGranahan, 2015). Engineers also frequently prioritise conventional sewers and wastewater treatment in masterplans without adequately considering the feasibility of maintenance or their suitability to serve lower-income households (Strande et al., 2023).

There is growing recognition of an OSS as a long-term solution rather than a temporary fix before transitioning to sewerage (Lüthi & Narayan, 2018; Strande et al., 2023). Achieving the SDG target 6.2 of safely managed sanitation for all by 2030 requires a fivefold acceleration in progress that cannot be achieved with sewers alone and requires radical improvements in OSS services (Berendes et al., 2017; Herrera, 2019). OSSs must be incorporated into urban sanitation planning as part of a mixed-technology approach, as advocated within the CWIS framework (Gambrill et al., 2020; Schrecongost et al., 2020) (see Box 3.1).

Box 3.1 OSSs in the CWIS approach

The CWIS approach emphasises the need to integrate OSSs and decentralised systems with sewerage to deliver services to the entire city, addressing the diverse and often complex realities of LMICs (BMGF et al., 2017). By advocating for technology-agnostic planning, CWIS focuses on achieving service outcomes based on feasibility considerations, including financial, environmental, political, organisational capacity, and cultural factors (Schrecongost et al., 2020). While OSSs are central to the CWIS approach for inclusive and equitable sanitation, their explicit focus on public health as a core criterion or objective is limited. Although safety is one service outcome in the CWIS service framework defined by Schrecongost et al. (2020), it is defined as protecting public goods for customers, workers and communities without evident emphasis on broader public health outcomes. In contrast, the World Bank definition underscores that CWIS projects should ensure service delivery outcomes meet user aspirations and protect health and that management of excreta across the service chain prioritises protecting environmental and human health (Gambrill et al., 2020).

3.3.2 Challenges in achieving safely managed on-site sanitation

Despite their widespread uses, significant challenges remain in ensuring OSSs are safely managed, particularly in dense urban areas. Some argue that OSSs were intended for use in sparsely populated areas and are less suitable for urban areas and less likely to achieve a safely managed service than sewers (Mara, 2018; Strande et al., 2023). Global data shows that only 52% of improved OSSs are safely managed compared to 79% of sewer systems (UNICEF and WHO, 2023). Excreta flow diagrams, also known as ‘shit flow diagrams’, (discussed in Section 3.4.2), offer insights into failures across the OSS service chain. A synthesis of excreta flow diagrams (SFDs) from 39 cities in Asia and Africa revealed multiple service chain failures for OSSs, which are summarised below and shown in Figure 3.4 (Peal et al., 2020).

- **Containment:** Around 59% of OSS users lack effective containment of excreta. Issues include discharge to open drains, water bodies or the surrounding environment (39%), leaching into the soil with significant groundwater contamination risks (17%), and unsafe abandonment of pits when full (2%). The definition of containment varies between SFD and Joint Monitoring Programme (JMP) monitoring, complicating assessment and comparisons.

- **Transport:** Of the population using OSS, only 39% had been emptied, and only a third were delivered to treatment. Of the effluent or supernatant discharged to open drains, less than a third (28%) reached treatment.
- **Treatment:** Around two-thirds (66%) of faecal sludge and supernatant delivered to treatment facilities is adequately treated. The remainder is reused without treatment or discharged to the environment.

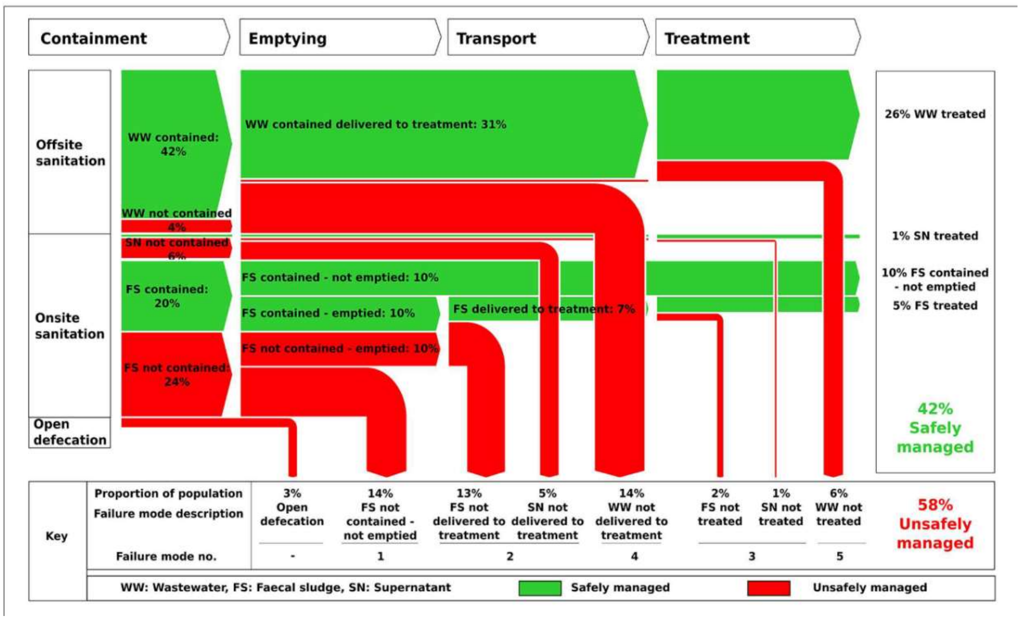


***Figure 3.4** Excreta flow diagram (SFD) for the 39 cities showing unsafely managed excreta (Peal et al., 2020)*

Numerous studies have demonstrated the multiple failures across the sanitation service chain and the release of untreated excreta into the environment. For example, a UN report on urban wastewater highlighted poor containment in septic tanks and inadequate faecal sludge treatment facilities in cities reliant on OSSs (UN-Habitat, 2023). Research in rural areas has identified similar gaps, such as issues with containment from pour-flush latrines, dry pits filling fast due to solid waste inputs, animal access to pits, safety issues during emptying and limited data or services for emptying and treatment (Nakagiri et al., 2015; Robinson & Peal, 2020). A systematic review of OSS emptying in LMICs in Asia found that although overall emptying rates were low, it was common for emptied sludge to be disposed into the environment and excreta to spill during transport, creating environmental and public health hazards (Conaway et al., 2023).

This section highlighted the important role of OSSs in global sanitation, particularly in LMICs, where they will continue to be an important solution to achieve safely managed sanitation for all. However, ensuring OSS services are safely managed remains a significant challenge, and critical failures across the service chain must be identified and addressed. This thesis focuses on addressing these challenges by contributing to a deeper understanding of OSS-related issues in LMICs. While tools like SFDs are valuable for identifying service chain weaknesses, integrating these engineering-based assessments with an analysis of health risks associated with different failure pathways could enable a more comprehensive approach to identify and prioritise investments that most effectively reduce public health risks.

3.3.3 Health risks associated with OSS failures

This section examines key public health risks associated with failures in the OSS service chain, focusing on exposure to faecal pathogens. While it addresses risks linked to containment and subsequent service steps, it excludes issues related to open defecation and use of shared facilities, which are extensively covered in the WHO Guidelines on Sanitation and Health (2018) and recent studies (Braun et al., 2024; Pessoa Colombo et al., 2023; Sprouse et al., 2024). Although exposure to faecal pathogens remains the primary focus, broader sanitation-related impacts, such as those linked to safety, dignity, poverty, stunting and education (UNICEF & WHO, 2020; WHO, 2018), are beyond the scope of this research.

3.3.3.1 Access to an improved toilet

Globally, 5% of households practice open defecation and 7% use unimproved toilets, with the highest prevalence in Sub-Saharan Africa, where 47% lack access to an improved toilet (UNICEF and WHO, 2023). Unimproved toilets include open pits, helicopter toilets, and toilets discharging to drains, which pose significant safety risks. Studies indicate that children in households with improved toilets were 17% times less likely to suffer diarrhoea (Merid et al., 2023) and use of unimproved sanitation is associated with higher odds of diarrhoea and diseases like hookworm and schistosomiasis (Adhikari et al., 2023). Pit latrines are classified as unimproved if they do not have a durable and easy-to-clean slab that fully covers the pit, increase pathogen survival or transmission via animals or fly vectors, and are at increased risk of collapse (Adhikari et al., 2023; Saxena & Den, 2022). Figure 3.5 demonstrates examples of different pit latrine slabs and the variation in surface type, cleanability and the pit coverage. Improved designs, like the provision of ventilation with fly covers, reduce odour and flies, although there remains limited literature linking the transmission of diseases by vectors from pit latrines to human exposure and outbreaks (Capone et al., 2023; Gwenzi et al., 2023).

Figure 3.5 *Unimproved (left and centre) and improved pit latrine with cleanable slab (right)*

(Source: Sustainable Sanitation, https://openverse.org/, licensed under CC BY 2.0)

Flush toilets are typically considered safer than pit latrines but still carry risks. Gooseneck toilets reduce exposure to excreta and animal access, lowering the risk of diarrhoea and gastrointestinal diseases compared to pit latrines (Adhikari et al., 2023). However, flush toilets discharging to open drains are considered unimproved and pose risks to both households and the community. The 2019 JMP progress report emphasised that the human right to sanitation includes both the right to access a hygienic toilet and, the right not to be negatively affected by other people's unmanaged faecal waste (WHO & UNICEF, 2019). This practice and the associated health risks are not well documented, as surveys often overlook the location to which excreta are discharged (Berendes et al., 2020). In India, direct discharge pipes release 10.5 $\log_{10}$ *E. coli* per person per day, higher than other failure pathways (Manga et al., 2022).

3.3.3.2 Pathogen reduction in OSSs

Inflows to OSSs include excreta, urine, flush water, cleansing water or materials, greywater, and occasionally solid waste and rainwater. Pathogen load depends on the prevalence of infection in the population, the pathogen shedding density and the number of users, while the concentration depends on the inflow volume (WHO, 2018). Higher and more diverse pathogens are shed in populations where diarrhoeal diseases and intestinal parasites are prevalent (Aw, 2019). Greywater, which includes water from bathing, washing, cooking and other domestic water uses, is sometimes discharged to the OSS, but in LMICs, it is often discharged to drainage systems, waterways or the ground (Manga et al., 2022; Morel & Diener, 2006). While lower concentrations of pathogens are expected in greywater compared to blackwater, the faecal contamination of greywater in LMICs has not been well studied (Morel & Diener, 2006). The addition of solid materials, including anal cleansing materials, menstrual hygiene products, or solid waste, varies widely depending on the toilet type and cultural practices. OSSs can also serve as reservoirs for emerging contaminants, including pharmaceuticals, microplastics, and multi-drug resistant *E. coli* (Gwenzi et al., 2023).

OSSs are designed primarily to store excreta and minimise human contact rather than to provide substantial treatment of pathogens. The pathogen reduction varies between types of OSSs due to the inflows, conditions in the containment, and design features. The main categories of OSSs covered in this thesis are described below and shown in Figure 3.6 (Tilley et al., 2014). However, it has been noted that classifications of OSS type are not consistent across literature or monitoring (Strande et al., 2023), and despite variations in function and risk, the type of OSS often is not specified in studies (Mbae et al., 2023). This review excludes less common containment types including composting and urine-diverting dry pit latrines, container-based sanitation and advanced treatment systems, such as prefabricated on-site treatment systems.

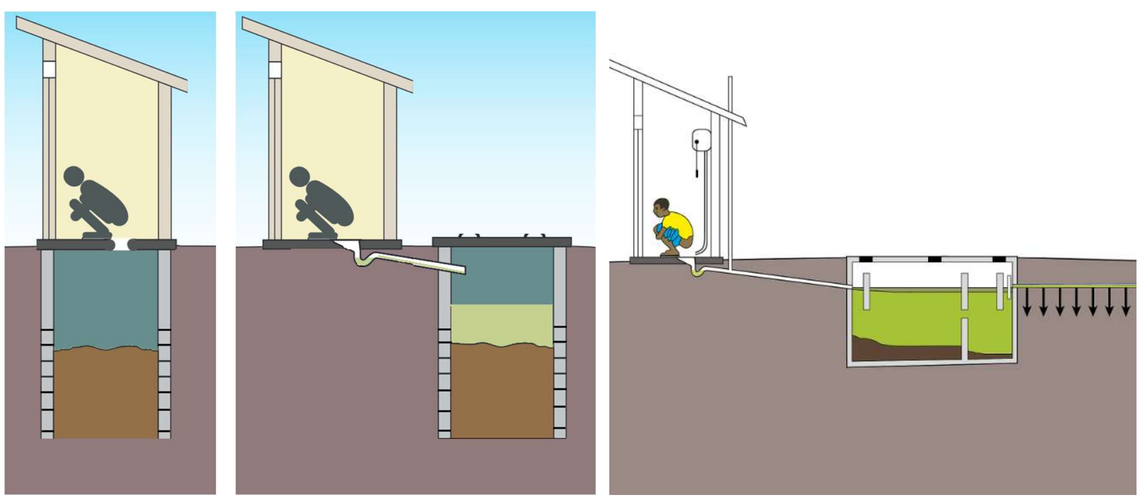


Figure 3.6 *Example of a dry pit latrine, cesspool (wet pit latrine) and septic tank with a leach field (adapted from Tilley, 2014)*

Dry pit latrines typically do not receive flush or greywater and are typically lined to prevent collapse but are permeable to allow liquids to infiltrate into the soil. Solids are stored and can either be emptied or the pit covered and a new one built. Pathogen reduction in dry pit latrines depends on decomposition and die-off, influenced by temperature, moisture and pH, with storage duration being the most critical factor (Musaazi et al., 2023; K. D. Orner & Mihelcic, 2018). Lower moisture levels accelerate pathogen decay, although the recommended moisture levels vary from 3% to 25% (Musaazi et al., 2023). Previous recommendations suggested pit latrine sludge was safe to handle after one year of storage, however, recent studies found pathogens present even after long-term storage (Musaazi et al., 2023; K. D. Orner & Mihelcic, 2018). After two years of storage, pathogens in sludge from twin pit dry toilets had been reduced by 2 $\log_{10}$, though *Ascaris* eggs may persist at low temperatures (WHO, 2023). Greater reductions were reported for urine-diverting dry toilets with added wood ash or lime, achieving a total reduction of viable protozoa and helminths and reducing viruses and bacteria by 4–6 $\log_{10}$ after 6–12 months (Stenström et al., 2011). Risks of exposure arise from passive contact (via flies or vectors), overflowing latrines, or during emptying (see below). Groundwater contamination is generally low due to low hydraulic loads, however, contamination can occur if the base of the pit contacts the groundwater.

Cesspools, or wet pit latrines, are single or twin semi-lined pits designed to store solids and allow liquids to infiltrate into the soil. They receive flushing water, anal cleansing materials or water but are unlikely to receive greywater. Solids can either be emptied, or the pit can be covered and an alternative used or a new pit built. Pathogen reduction in cesspools is slower than in dry latrines, as wet conditions hamper pathogen die-off. Less than 1 log reduction is typically achieved in single pits, while more than 2 log removal is possible (except *Ascaris* eggs) for alternating twin pits after 1.5–2 years of storage without fresh additions (WHO, 2023). A shorter storage time may be adequate under higher temperatures or pH>9, achieved by adding lime or ash (WHO, 2023). However, a study in rural Cambodia found that high faecal indicator bacteria concentrations remained in alternating pits even after two years, possibly due to incomplete mixing of lime or inadequate storage (Harper et al., 2023). Moisture levels depend on soil infiltration, and upper sludge layers may be covered in a water layer (as occurs in tanks) or exposed to air (similar to dry pits). Groundwater contamination risks increase due to hydraulic loads of inflows, which facilitates the transport of pathogens, however, studies on cesspools’ effects on groundwater are limited (Adegoke & Stenstrom, 2019a).

Septic tank systems are typically watertight, two-chamber tanks designed for settling and storing solids until regularly emptied, and discharge liquid effluent to a subsurface infiltration system. Inflows include flush water, anal cleansing water or materials, and greywater, although greywater inflows are less common for systems in LMICs. Pathogen reduction in septic tanks occurs mainly through subsurface infiltration or sludge treatment after removal, with limited treatment in the tank. Tanks are designed to settle solids by storage of liquids for at least 24 hours and to minimise the solids in effluent which could clog the subsurface infiltration system. Typically, 0–2 log reduction in pathogens can be achieved within the tank, with further pathogen removal in soil infiltration, influenced by the soil type and vertical separation with groundwater (WHO, 2018). A recent review of literature on pathogen reduction in septic tanks suggested 4–8 log pathogen reductions, yet these removals were from more advanced treatment systems than those commonly used in LMICs (Adegoke & Stenstrom, 2019b; M. Wang et al., 2021). In urban India, septic tank effluent had *E. coli* concentrations of 7 log_{10} MPN/L, with concentrations in sludge ranging from 6.7–7.7 log_{10} MPN/L (Manga et al., 2022). Reduction is most effective for helminth and protozoa, as they have a higher settling velocity than bacteria and viruses (M. Wang et al., 2021).

3.3.3.3 Containment of excreta in OSSs

Discharge of effluent to drains or overflow of OSSs to the surface environment

Global monitoring of safely managed sanitation for SDG 6.2 classifies OSSs as uncontained if they discharge or overflow to the surface environment (UNICEF and WHO, 2023). As noted above, with minimal pathogen treatment, any excreta or effluent released from an OSS is unsafe and requires further treatment. Septic tanks, designed to discharge effluent to subsurface infiltration, may instead have outlets to drains, waterways, or surface environments. Direct discharge can also occur with cesspools due to watertight lining, poorly draining or clogged soils, or shallow groundwater. In 39 African and Asian cities, 39% of OSSs discharged directly to open drains or waterways (Peal et al., 2020). Studies in urban areas of India and Vietnam found 60%–98% of septic tanks discharged to open drains or sewers not connected to treatment (Dasgupta et al., 2021; Harada et al., 2008; Manga et al., 2022). Even in HICs like Ireland and the USA, direct discharge is reported and contributes to significant faecal contamination (Richards et al., 2016a; Withers et al., 2014).

Discharge from OSSs to surface waters poses a significant risk to the entire community. Various studies show that in urban areas, pathogen exposure is highest from open drains compared to drinking water, soils or other pathways (Coulibaly et al., 2023; Katukiza et al., 2014; Y. Wang et al., 2022). Environment sampling in India and an urban flood model in Uganda highlight that OSS discharge to drains contribute more pathogens to the environment annually than other failures, such as the dumping of faecal sludge (Manga et al., 2022; Okaali et al., 2019). Flooding can exacerbate risks, spreading contamination within and beyond the community (Okaali et al., 2019).

Overflowing OSS, which can be exacerbated due to infrequent emptying, exposure to flooding, or more users than designed, was frequently reported in dense areas in Nigeria, Ghana and Kenya (Oduah & Ogunye, 2023). Climate change and extreme weather further exacerbate flooding and can cause washout of excreta, and several studies suggest households intentionally flush out OSSs during floods (Hyde-Smith et al., 2022; Jenkins et al., 2015; Williams & Overbo, 2015).

Groundwater risks associated with OSS

Global monitoring under SDG 6.2 does not consider groundwater risk in estimates of containment. However, this is an area of significant research concerning the health risks associated with OSS. Several systematic reviews show that pathogen removal in soils and groundwater varies significantly with hydrogeological conditions, with removal rates varying with soils and aquifer type, for example, removal in sands and limestones was a minimum of 10^{-4} log/m while clayey soils had up to 10^{0} log/m microbial removal rates (Pang, 2009). Transport also varies by pathogen; viruses travel further than helminths and protozoa, which are often trapped by soil (Graham & Polizzotto, 2013; Pang, 2009). Setback distances between OSSs and wells range from 10m to 50m but often lack empirical validation (Nenninger et al., 2023). Graham and Polizzotto (2013) emphasise the need to test current siting guidelines empirically. Nenninger et al. (2023) conclude that modelling could provide more useful location-specific setback distances than a one-size-fits-all approach.

Horizontal separation from sanitation facilities is not the only factor influencing well contamination; vertical separation between the pit base and groundwater is also critical. Greater pathogen removal is expected in the unsaturated soils, while shallow groundwater was associated with increased pathogen counts and travel distances (Mbae et al., 2023). Nenninger et al. (2023) conclude that vertical separation may be more important than horizontal separation; however, few guidelines include vertical separation limits. Factors like rainfall, seasonality and population density also influence contamination (Back et al., 2018; Genter et al., 2023; Murphy et al., 2020). A recent review and an empirical study in Bangladesh highlight multiple pathways for well contamination and note that studies on OSS contribution often fail to control these variables effectively (Mbae et al., 2023; Ravenscroft et al., 2017).

3.3.3.4 OSS filling and emptying

Understanding OSS filling rates and what happens when systems are full is essential to assess associated risks. Filling rates depend on inflows, OSS type, and environmental conditions. Dry pits, with aerobic and anaerobic degradation, accumulate sludge at higher rates (21–81L/cap.yr from studies in Africa) compared with wet pits (13 L/cap.yr from one study in India) (Byrne et al., 2017; Lugali et al., 2016; Prasad et al., 2021; Still & Foxon, 2012). Septic tank filling rates have varied, with studies in South Africa, India and Vietnam reporting from 22–37 L/cap.yr (Moonkawin et al., 2023; Prasad et al., 2021; Still & Foxon, 2012), whereas in Ireland, much higher rates were reported (100 L/cap.yr), potentially due to greywater inflows and colder climates (Mahon et al., 2022). While some studies have reported high accumulation rates (150–280 L/cap.yr) (Strande et al., 2018), the methods indicate these are the total volume emptied and not the settled sludge layer (Prasad et al., 2021). Factors that influence sludge accumulation rates include diet, anal cleansing materials, pH, available oxygen, temperature, moisture and non-degradable matter (Still & Foxon, 2012).

Septic tanks require regular emptying every 2–5 years to maintain adequate hydraulic retention (Mehta et al., 2019). However, many studies report infrequent emptying, with over 80% of tanks in studies in Asia never emptied and emptying intervals ranging from 8 to 16 years (Conaway et al., 2023; Moonkawin et al., 2023). While frequent emptying is known to reduce TSS and COD in effluent, data on its effect on pathogen discharge is limited, although longer hydraulic retention times have been associated with improved effluent quality (Manga et al., 2022; Richards et al., 2016a).

Pit latrine emptying practices vary, with some pits regularly emptied due to solid waste or a high water table (Peletz et al., 2020), while others can remain unemptied for over 18 years (Jenkins et al., 2015). Full pits risk overflow or reverting to open defecation, although some households continue to use full pits due to unavailable or expensive emptying services and lack of space to build a new pit (Nakagiri et al., 2015). Alternating twin pit latrines assume sludge is safe to empty after two years of undisturbed storage, although a recent study suggests this may be insufficient, especially when the system is not operated as intended (Harper et al., 2023).

Sanitation workers involved in emptying face significant health hazards. While both mechanical and manual emptying present risks, mechanical emptying is typically considered safer (Conaway et al., 2023). Manual emptying often involves entering the pit to remove sludge with a shovel, which poses multiple risks, such as skin infections and gastrointestinal disease, risk of pit collapse or inhalation of harmful gases (Muoghalu et al., 2023). Measures such as manual pumps, training, protective equipment, and healthcare aim to improve worker safety (World Bank, WHO, et al., 2019).

3.3.3.5 Emptied sludge, treatment and reuse

The greatest risk during transport and treatment is the direct discharge of sludge into the environment, as reported by several studies (Conaway et al., 2023). An assessment of 39 cities found only 35% of emptied sludge was disposed in a treatment facility, with the rest discharged to the environment (Peal et al., 2020). Sludge quality varies, particularly in terms of solid content and level of degradation, but typically contains high pathogen concentrations (Velkushanova et al., 2021). For example, *E. coli* concentrations in emptied sludge in India ranged from 5.5 $\log_{10}$/L for lined pit latrines, 6.7–7.7$\log_{10}$/L for other tanks, and up to 8.2$\log_{10}$/L for fully lined community tanks (Manga et al., 2022). Reviews of faecal sludge management in LMICs in Asia, reveal that direct discharge, often to canals, water bodies, public or agricultural land, is a primary pathway for environmental releases (Conaway et al., 2023).

Sludge discharged to treatment is typically high strength and partially digested, necessitating both solid and liquid treatment before release to the environment. Sludge can be processed in a dedicated sludge treatment plant, discharged to a wastewater treatment plant, or combined with organic waste in a composting plant (Tayler, 2018). Safely managed sanitation requires that wastewater or liquids from sludge receive at least secondary treatment, which does not necessarily achieve pathogen removal, therefore risks may still remain depending on the eventual end use or disposal (WHO, 2018). Risks during treatment primarily stem from overloading, malfunction, bypass or overflow (WHO, 2018).

This overview emphasises the significant health risks present at all stages of the OSS service chain. The effectiveness of pathogen removal varies widely between OSS types, yet these distinctions are often poorly classified or not reported in research. Unsafe practices and poor operation and management are common, and external factors such as flooding can further intensify these risks, underscoring the complexity of the challenges faced. While not all risks are expected to be present in all contexts, many studies narrowly focused on single failure or exposure pathways. Beyond SFDs, systematic assessments of risks across the entire chain are lacking, and inconsistent methodologies to assess risks hinder meaningful comparisons. Building on Cairncross et al. (2010) recommendations, robust data linking environmental health risks with sanitation systems and failures is essential for advocacy and informed decision-making. Furthermore, monitoring indicators of risks can strengthen the evidence base for designing interventions, programs and policies that are not only more effective but also equitable (Cairncross et al., 2010).

3.4 Assessing and monitoring risks of OSSs

Considering the public health engineering perspective, this section outlines the differences between health and engineering approaches to assessing risk and outlines the types of data required for each. It also provides a summary of current approaches to assess and monitor the health risks of OSSs from these two perspectives.

In this thesis, I distinguish between **assessing and monitoring risks** and **risk assessment**, acknowledging that these terms can have varied interpretations across sectors and uses. Drawing on the WHO Sanitation Safety Planning guide and UN-Water's publication on sanitation, wastewater management and sustainability, I define **assessing risks** as a detailed, often one-time analysis aimed at identifying actual or potential risks within the sanitation system to understand the source and extent of risks, while **monitoring risks** refers to an ongoing process of tracking identified sanitation and health-related parameters over time or during system operation (Andersson et al., 2020; WHO, 2023). For example, **assessing risks** could include an empirical study investigating risks associated with a specific sanitation system or transmission pathway, while a local or national household survey to track sanitation or health-related indicators would be an example of **monitoring risks**. Both focus on the data collection and identification of risks but differ in purpose and frequency.

Beyond the identification of risks, **risk assessment** methodologies evaluate, compare and prioritise risks, often by quantifying their probability and analysing potential consequences. These vary in degree of complexity and data requirements, including qualitative risk assessments, such as team-based or community assessments that could be done for water and sanitation safety planning, semi-quantitative ranking risks through matrices of likelihood and severity, and quantitative methods, such as QMRA (further discussed in Section 3.4.2 below) (WHO, 2023). While this briefly addresses risk assessment methodologies, its primary focus is on the data requirements for various approaches, rather than an in-depth review of the methodologies themselves.

3.4.1 Health and engineering approaches to assessing risks

Different sectors adopt distinct approaches to risk assessment, each requiring specific data and inputs. This section outlines the objectives and methodologies of engineering and public health approaches to risk assessment and explores how these inform data needs and decisions derived from the assessment.

An **engineering approach to risk assessment** prioritises system safety and functionality. Risk assessments in this context aim to identify hazards or failure events (e.g. sanitation service chain failures) and evaluate risks, typically defined as the product of likelihood (or probability) and consequence (or impact). The primary goal is to identify system vulnerabilities and inform the design of mitigation measures, such as structural improvements or the inclusion of safety factors to ensure risk remains below acceptable thresholds (Modarres, 2006). This approach emphasises (i) identifying critical points of failure in the sanitation system, (ii) quantifying risks to prioritise design improvements, and (iii) informing engineering solutions to improve system reliability and safety.

A **public health approach to risk assessments** focuses on the exposure to harmful elements and associated health outcomes. This approach identifies potential health hazards (e.g. specific contaminants or pathogens) and evaluates risk based on the dose-response relationship and the magnitude, duration and frequency of exposure. Public health risk assessments often quantify the expected health outcomes (e.g. illness or mortality rates) and aim to inform interventions, regulations or behaviour change to reduce the risk (EnHealth, 2012; Frumkin, 2016). This approach emphasises (i) identifying specific health hazards, often through environmental monitoring or epidemiological studies, (ii) evaluating the relationship between exposure levels and health outcomes, and (iii) developing interventions and policies to reduce exposure and associated health risks.

Both approaches are valuable for assessing the health risks of sanitation. The engineering approach provides insights into the structural or operational aspects of a system that contribute to hazards, enabling the identification of practical mitigation actions. Whereas the public health approach highlights that not all hazards have equivalent consequences and quantifies health outcomes, emphasising the non-linear relationship between exposure concentration and illness. As detailed in Box 3.2, the Sanitation Safety Planning (SSP) risk assessment tool incorporates elements from both engineering and public health perspectives, emphasising the importance of tailoring risk assessment methods to the available data and technical capacity. By integrating these perspectives, a more comprehensive assessment of risk is possible that addresses the complexities of sanitation failures and transmission pathways and can better inform interventions to address these risks.

Box 3.2 WHO Sanitation Safety Planning (SSP) definition of hazards and risks

The **WHO Sanitation Safety Planning (SSP)** framework defines **risk** as the combination of the likelihood and consequences that something with a negative impact will occur (WHO, 2023). **Hazards** are described as biological, chemical or physical constituents, or acceptability aspects, that can cause harm to human health. **Hazardous events** are incidents or situations that (i) introduce or release a hazard to the environment in which humans are living or working, (ii) amplify the concentration of a hazard in the environment, or (iii) fail to remove a hazard from the human environment. A single hazard may be due to multiple hazardous events with different causes, requiring different approaches to risk mitigation. The risk of infection from faecal contamination depends on the likelihood of exposure and the impact of the pathogen hazard on the person exposed. Hazards do not pose a risk without exposure. Reducing risks from faecal contamination involves lowering the faecal pathogen hazard level (i.e. concentration or numbers of the pathogen) and/or minimising human exposure to the hazard (WHO, 2018, 2023). The SSP guidance outlines different approaches to assess these hazards and risks, including both desktop and qualitative methods, as well as approaches for semi-quantitative or quantitative assessments.

The data and methods for assessing and monitoring sanitation risks discussed in this thesis provide inputs required for risk assessment tools, such as the SSP. For example, data collected through monitoring or assessment of risks can inform the steps 1 to 5 of implementing a SSP shown below.

Six modules of sanitation safety planning (WHO, 2023).

1. Where should SSP be done? Who should be involved and what are their roles?
2. How does the sanitation service chain work? Who is at risk?
3. What could go wrong? What existing control measures are in place and how effective are they? How significant are the risks?
4. What needs to be improved and how?
5. Is the sanitation system operating as intended? Is it effective?
6. How should SSP be supported? How can we adapt to changes?

3.4.2 Current methods for assessing and monitoring sanitation risks

This section summarises the literature on assessing and monitoring health risks associated with OSSs to identify how sanitation technologies and their implementation contribute to faecal contamination of the environment. The review focuses on methods to identify and quantify potential sources of risks and hazards through assessing or monitoring risks. As noted at the start of Section 3.4, risk assessment tools are generally excluded as I focus more on the generation of risk data than comparisons, however, the following section includes quantitative microbial risk assessment (QMRA) which is a risk assessment methodology since it combines the environmental contamination and exposure with frequency and severity.

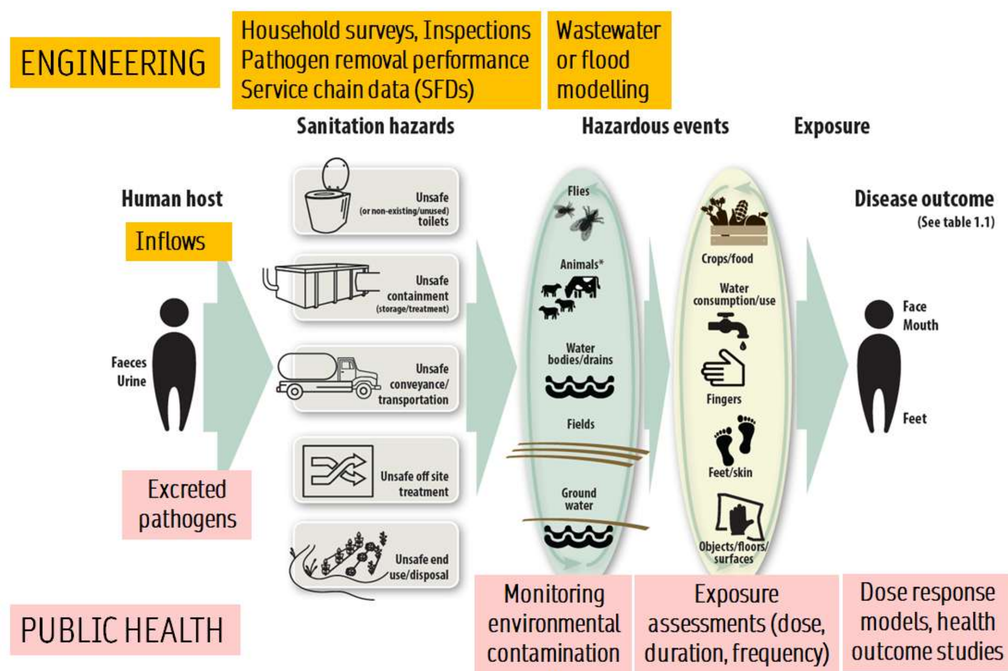


Figure 3.7 *Engineering and public health monitoring across F-diagram*

Engineering and public health-based approaches to assessing and monitoring risks have different scope, objectives and inputs. For example, the scope of public health risk assessments would typically focus more on human interactions with hazards than identifying the technical issues contributing to the hazard. Engineering assessments may stop at physical or technical aspects of impacts without translating those to human health outcomes. Mapped onto the F-diagram in Figure 3.7 are some approaches to assessing and monitoring risks and their focus on sanitation failures, events and exposure and whether they are more of a technical or engineering assessment or a public health approach, recognising that these methods have overlaps and broader objectives. It is not a detailed review of the methods but more a summary of the scope and use of common approaches.

3.4.2.1 Engineering approaches to monitoring risks from OSSs

Understanding and mitigating risks from OSSs requires understanding how sanitation systems function and where failures occur. The methods summarised below provide insights into different aspects of sanitation systems that can be assessed with different methods and lenses. The assessments can quantify the extent to which different hazards occur, the locations and types of systems where failures are more common, and the potential for human exposure by data on where excreta are discharged and in what quantities. This review also aims to reflect on any challenges or limitations of the methods, such as data gaps and assumptions, variability or uncertainties in methodologies, and the local capacity required for effective implementation. The approaches include household questionnaires, sanitation inspections, technology assessments, service chain assessments, flow models and service delivery assessments.

Household questionnaires: Household surveys are a cornerstone for global monitoring of the SDGs, providing estimates of sanitation access and type, particularly in LMICs where administrative data is lacking. These surveys typically rely on self-reported data regarding access to toilets, type of toilet, availability of handwashing facilities, and illnesses such as diarrhoea. Although valuable for capturing nationally representative data that can be disaggregated to analyse inequalities from the socio-economic data collected, there are limitations. Self-reported information may not accurately reflect system functionality, and desirable response bias further complicates data reliability (Bartram et al., 2014). Terminology for types of sanitation technology or issues may not be harmonised between local and global definitions, and many features may be unknown as OSSs are mostly hidden beneath the ground. For instance, in Cambodia, OSSs were historically labelled as ‘septic tanks’ but recent surveys with improved definitions and training of enumerators revealed most systems were cesspools, which significantly altered the assessment of risk (WHO, 2024). In the absence of local data, global estimates for SDG monitoring rely on assumptions about containment: 100% of pits are assumed to be contained while it is only 50% for septic tanks. While updated tools like UNICEF’s Multiple Indicator Cluster Survey (MICS) now include questions on containment and emptying (UNICEF, 2023), quality results require adequately trained enumerators and careful translation of sanitation terminology.

Sanitation inspections are standardised observational assessments of risks associated with toilets or containment systems. Using standardised inspection forms, such as the observation guides and graphics developed by WHO (Figure 3.8),**Error! Reference source not found.** trained inspectors identify hazards, assess risks, and recommend mitigation measures (WHO, 2022). National sanitation inspection programs exist in Ireland and France, where regular inspections are required as part of environmental protection laws in Ireland and service provision requirements in France (EPA Ireland, 2021; PANAC, 2014). The sanitation inspections user guide outlines these and other uses of inspections for different regulatory environments (WHO, 2024). Inspections require access to sanitation facilities to visually assess potential hazards and personnel with some environmental health training, which may make widespread implementation in LMICs challenging. However, they provide a more reliable assessment of risk than self-reported data and can directly inform risk mitigation activities.

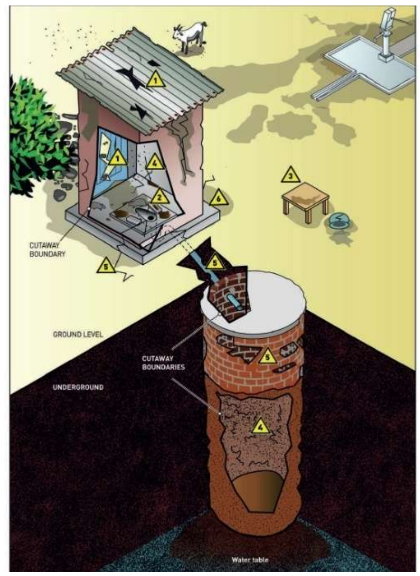


Figure 3.8 *WHO Sanitation inspection form for cesspools*

Assessment of sanitation technology performance: Laboratory and field studies on sanitation technologies help evaluate system performance, identify risks or assess improvement options. For example, technology assessments have assessed pathogen degradation processes in septic tanks and examined factors like hydraulic retention time, baffle design, temperature and desludging intervals (Appling et al., 2013; Cheng et al., 2023; Koottatep et al., 2013; Sharma et al., 2014). Various studies have characterised the microbiological treatment zones in pit latrines (Capone, Chigwechokha, et al., 2021; Ijaz et al., 2022; Smith et al., 2023). Studies on sludge properties have also informed emptying and treatment processes, highlighting high variability influenced by containment type, demographics, and environmental and technical factors (Englund et al., 2020). While these assessments provide detailed insights into risks, they are resource-intensive and often focus on specific systems or locations, and the generalisability of findings may be limited.

Service chain assessments evaluate the management of excreta from the toilet through containment, emptying, transport, treatment and disposal. Tools like the excreta flow diagram (SFD) visualise the fate of different excreta streams in a city, demonstrating the population using safely managed sanitation systems (see green horizontal arrows in Figure 3.9) and those with not safely managed systems (red down arrows). While not specifically a data collection method, they often rely on limited data, requiring semi-quantitative methods like interviews and transect walks (SFD Promotion Initiative, 2018). SFDs, therefore, often provide the first assessment of how excreta from OSSs are managed across the service chain. They are valuable in providing a clear visual summary of service gaps and are recommended to be linked with the institutional aspects of service delivery from the service delivery assessment described below (Peal et al., 2020).

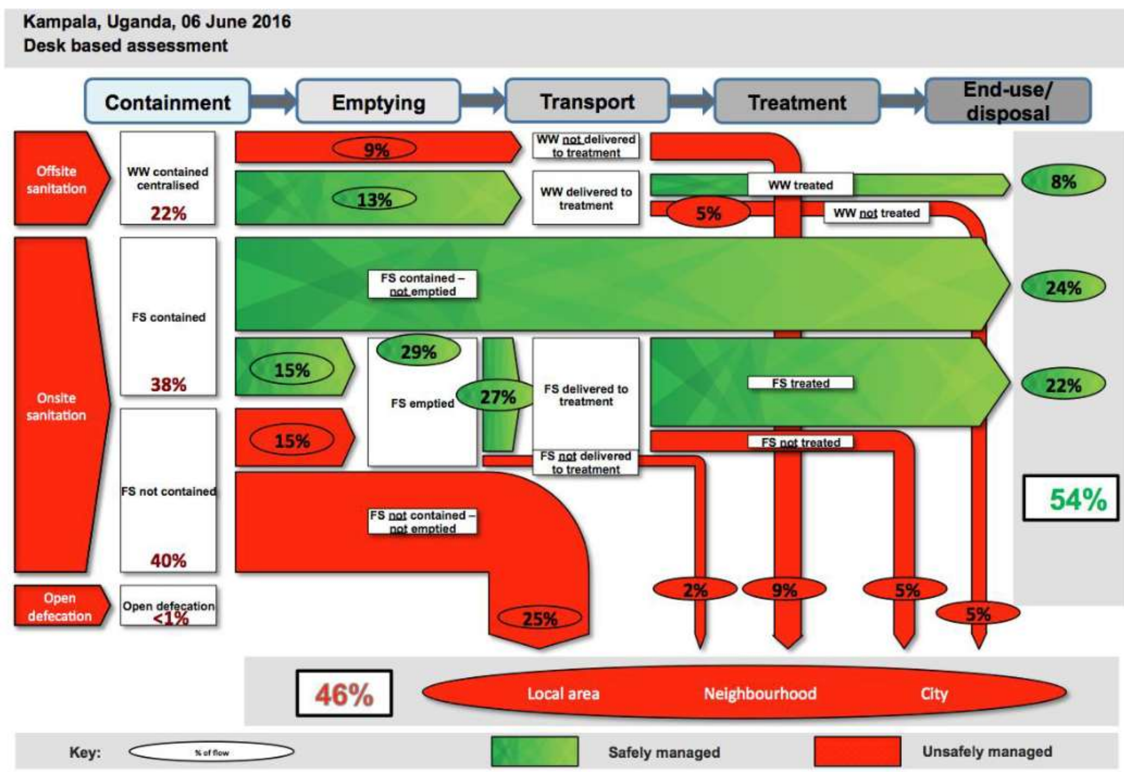


Figure 3.9 Example of an excreta *f*low *d*iagram showing the horizontal green flows that are safely managed and the vertical red arrows that are unsafe.
(Schoebitz et al., 2016)

Global monitoring for SDG target 6.2 also includes assessment of the excreta management across the service chain. It uses national data such as household surveys or administrative data to estimate the population accessing safely managed sanitation. While many countries have data on OSSs that are never emptied and safely stored in-situ based on household survey data, additional data sources from service providers or regulators are needed to assess transport, treatment and disposal. The 2023 update could only estimate the proportion of safely emptied and treated off-site for five high-income countries (UNICEF and WHO, 2023). There are differences in how the SDG and SFDs assess safe management, with the SDGs including only unshared improved toilets as potentially safe, while the SFD considers groundwater risk but does not assess sharing (SFD Promotion Initiative, 2018).

Pathogen flow and flood modelling can provide valuable insights into how sanitation failures lead to pathogen dispersion and exposure. Models have been used to simulate floodwater contamination and exposure in Kampala and Dhaka (Mark et al., 2018; Okaali et al., 2019), pathogen discharge and comparative health impacts of improvement options in Dhaka (Foster, Falletta, et al., 2021), and groundwater risks and subsurface pathogen movement (Nenninger et al., 2023). They offer a nuanced understanding of the complex interactions between sanitation systems, the environment and transmission pathways. For example, the combined urban flood and QMRA model in Dhaka identified direct floodwater contact as a plausible route for the primary transmission of cholera (Mark et al., 2018). While models are valuable for assessing pathogen transport and exposure due to sanitation failures, they require significant local data and a sound understanding of contamination processes for high-quality models and meaningful outputs.

Service delivery assessments evaluate the enabling environment for OSS service delivery, considering regulatory frameworks, capacity, and service availability. Tools like the City Service Delivery Assessment and Sanitation 21 Framework analyse institutional factors affecting sanitation delivery, helping prioritise actions to improve services (Schertenleib et al., 2021). The SSP tool, also described in Box 3.2, brings stakeholders together to assess health risks along the sanitation chain and to identify priority improvements, responsible actors and regular monitoring and review (WHO, 2023). While these assessments provide valuable insights into systemic challenges, they focus more on institutional factors than technical system performance. Integrating service delivery evaluations with technical assessments can offer a more comprehensive understanding of risks.

3.4.2.2 Health approaches to monitoring risks from OSSs

This section summarises the approaches to assessing and monitoring environmental contamination and health risks related to on-site sanitation. Health-based approaches to assessing sanitation risks focus on human exposure to contamination pathways, and some also aim to quantify health outcomes. This section summarises environmental monitoring, exposure studies, quantitative microbial risk assessments (QMRA), and health impact studies, highlighting their contributions and challenges to assessing sanitation risks.

Environmental monitoring related to sanitation involves detecting pathogens in different transmission pathways, such as drains, recreation waters, drinking water, soil, surfaces or hands. These assessment studies often aim to identify the presence and/or concentration of pathogens in different pathways, which are then analysed in relation to sanitation infrastructure (Berendes et al., 2018; Manga et al., 2022) or exposure pathways (Y. Wang et al., 2022). Advances in pathogen detection methods, such as wastewater-based epidemiology, have increased the feasibility of these studies in LMICs, particularly during the COVID-19 pandemic. However, surveillance is more often used to inform public health responses (i.e. vaccinations, or the presence of polio) rather than sanitation interventions (Delgado Vela et al., 2024; Hamilton et al., 2024). There are many opportunities for further application of environmental monitoring in the context of LICs which could improve understanding of health risks associated with OSSs, particularly in informal settlements where the interactions between sanitation and drinking water are high (Gwenzi et al., 2023).

Exposure studies assess both environmental contamination and human interactions with transmission pathways. Human interactions with the environment can be assessed through survey data on self-reported behaviours or observation data that assess the frequency and sometimes also duration of interactions with different pathways (Goddard et al., 2020). The SaniPath tool provides a systematic approach to quantifying human exposure to faecal contamination through behavioural surveys and analysis of *E. coli* concentrations in the environment (Raj et al., 2020). It allows comparison of exposure risks for different pathways, such as drinking water, bathing, surface water, open drains, floodwater, raw produce, street food, and shared toilets. However, it does not identify the sources of contamination. Other studies that have assessed sanitation risk based on monitoring specific exposure pathways, including via soil, flies, food and drains (Berendes et al., 2020; Capone, Berendes, et al., 2021; Capone et al., 2023; Doza et al., 2018). These assessments provide essential data on how behaviours and environmental contamination intersect and which exposure pathways to investigate further. While costly and time-intensive, more data on dose and exposure in LICs would provide better estimates of exposure, particularly related to drain and flood exposure.

Quantitative microbial risk assessments (QMRA) go beyond exposure by integrating dose-response relationships to estimate the probability of infection and illness and sometimes disability-adjusted life year (DALY) from specific pathogens. It can be used to estimate the likelihood of illness from exposure to different pathways, for different actors (e.g. pit emptying or treatment plant workers) and to estimate pathogen reductions needed to meet health-based targets (Fuhrimann et al., 2016; Jean-Baptiste & Monette, 2024; Katukiza et al., 2014; Mraz et al., 2021; WHO, 2015). While valuable for risk estimation and comparison, its application in LMICs is constrained by the high cost of microbiological testing, the need for locally relevant data on exposure and ingestion volumes, and the suitability of dose-response and infection models to more vulnerable populations with frequent exposure to pathogens, as occurs in low-income countries (Harder et al., 2017; Van Abel & Taylor, 2018).

Controlled trials, including randomised control trials (RCTs), are widely used in the health sector to assess health outcomes of interventions and are perceived as high-quality methods to assess benefits and risks. Large scale studies, such as the WASH Benefits trials and recent RCTs in Bangladesh, India, Mozambique and Zimbabwe, tested the impact of improved toilets on child health but found limited evidence linking household latrine improvements with the prevention of diarrhoea or improved ground among children (Clasen et al., 2014; Cumming et al., 2019; SHINE et al., 2015). As discussed in Section 3.2.1, the results do not suggest that sanitation has no impact on health outcomes but instead that the relationships are complex, with multiple transmission pathways that are difficult to monitor (Contreras & Eisenberg, 2019; Cumming et al., 2019; Whittington et al., 2020). Given the high cost of these studies, Capone (2020) suggests that a first step to understanding health risks from sanitation could be to focus first on how effectively interventions reduce environmental faecal contamination as a precursor to health outcomes.

These health-based approaches to monitoring OSS risks enable the assessment of environmental contamination, exposure via different transmission pathways, and approaches to estimate health outcomes. However, studies on the source of contamination and sanitation’s role often rely on toilet access metrics, overlooking failures and excreta release across the sanitation service chain. Additionally, health monitoring in many LMICs remains challenging due to capacity, infrastructure and financial constraints; limitations in data and approaches developed for populations in HICs and low pathogen concentrations; and the complexity of multiple potential sources of faecal contamination.

3.5 Summary

While poor sanitation is undeniably associated with diarrhoeal diseases, the drivers for sanitation investments have shifted away from health outcomes to instead prioritise environmental hazards, resource recovery and finically sustainable service delivery. This shift was largely driven by improved sanitation infrastructure and reduced excreta-related public health outbreaks in HICs, which contrasts with conditions in many LMICs, where the burden of faecal-related diseases and poor sanitation remains high. The first section of the review, including Paper 1, highlights the critical need to re-prioritise health as a core driver of sanitation investments and highlights significant data gaps that limit health-based decision-making.

The second section examines ongoing health challenges in LMICs and the complexities of evaluating how sanitation improvements contribute to public health outcomes. Many controlled trials often assess sanitation interventions by focusing narrowly on access to improved toilets, overlooking the multiple exposure pathways that influence health outcomes. These studies often fail to consider the evidence widely understood in the engineering sector and included in the SDGs, that safely managed sanitation requires excreta management across the entire service chain, which cannot be assessed by only monitoring toilet access. The review underscores the need for integrated approaches that combine engineering and public health perspectives to comprehensively assess risks and failures, considering infrastructure design, in-situ operation, and the various releases and exposure pathways across the service chain.

The review demonstrated the increasing global reliance on OSSs, alongside evidence of their multiple failures and associated health risks. Despite their widespread promotion as a safe urban sanitation solution, OSS are often implemented without adequate consideration of contextual factors, leading to unmanaged excreta and increased health risks. The rapid construction of OSSs to expand basic access often neglects operational requirements and service availability necessary to ensure safe excreta management. While numerous studies demonstrate OSS failures, there is a paucity of literature on the fate of pathogens from OSSs and how different OSS types and failures contribute to public health risks. This gap in understanding the health risks of OSSs limits decisions to effectively reduce risks, particularly in LIC urban areas, where pathogen exposure remains high.

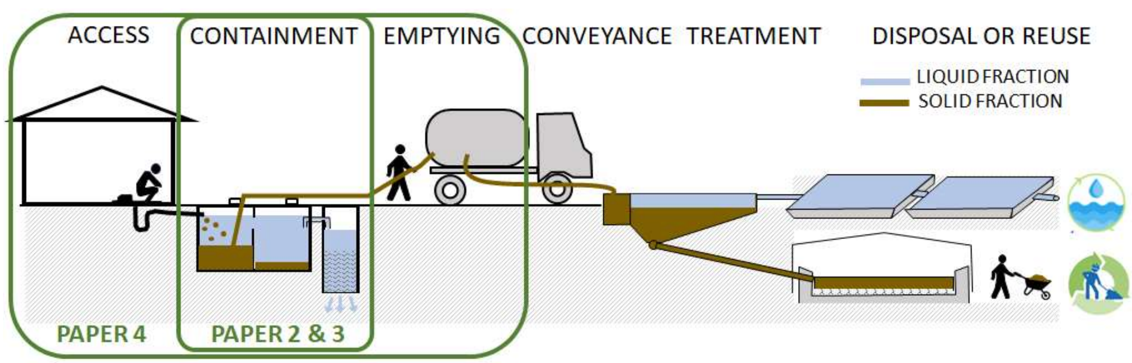
To address these gaps, this thesis identifies critical pathways where integrated assessments of sanitation functionality, implementation, and health risks are most needed. Paper 2 investigates the risks associated with OSS discharges into open drains in Dhaka, Bangladesh, while Paper 3 examines groundwater contamination risks from OSSs in Metro in Indonesia. These studies apply innovative methods that merge engineering and health approaches to assess risks in diverse contexts, providing new evidence on the severity and contributing factors to different failure pathways. Additionally, the research explores how advances in technologies to measure pathogens in the environment can improve sanitation risk assessment in LMICs.

Beyond localised empirical studies, broader scale assessment are also needed, as national and global decision-making cannot rely solely on context-specific studies. Despite the numerous risks identified in the review, existing approaches to assess sanitation across the service chain, such as SDGs and SFDs, primarily focus on environmental outcomes and service management, often neglecting many potential health risks. This omission results in an incomplete, and somewhat misleading, assessment of 'safely managed sanitation'. The thesis aims to also address these gaps by contributing new methods to assess and monitor risks. This includes empirical methods in Paper 2 and 3, while Paper 4 presents a systematic and standardised approach to assess multiple risks through household surveys which can be integrated into local, national or global monitoring efforts across urban and rural settings.

This literature review forms the foundation of the thesis, shaping the direction of the three research papers. Each paper builds on the review by providing specific insights into sanitation risks, failures, and assessment methods, relevant to the failure pathway and context of each study.

PART III
RESULTS

- Chapter 4 – Paper 2: *Unsafe containment: Public health risks of septic tanks discharging to drains in Dhaka Bangladesh*
- Chapter 5 – Paper 3: *How do sanitation siting criteria in urban areas relate to well contamination in shallow groundwater in Indonesia*
- Chapter 6 – Paper4: *Indicators to complement global monitoring of safely managed on-site sanitation to understand health risks*



Sanitation service chain for on-site sanitation showing the research focus on the access, containment and emptying steps.

4. Paper 2

Unsafe containment: Public health risks of septic tanks discharging to drains in Dhaka Bangladesh

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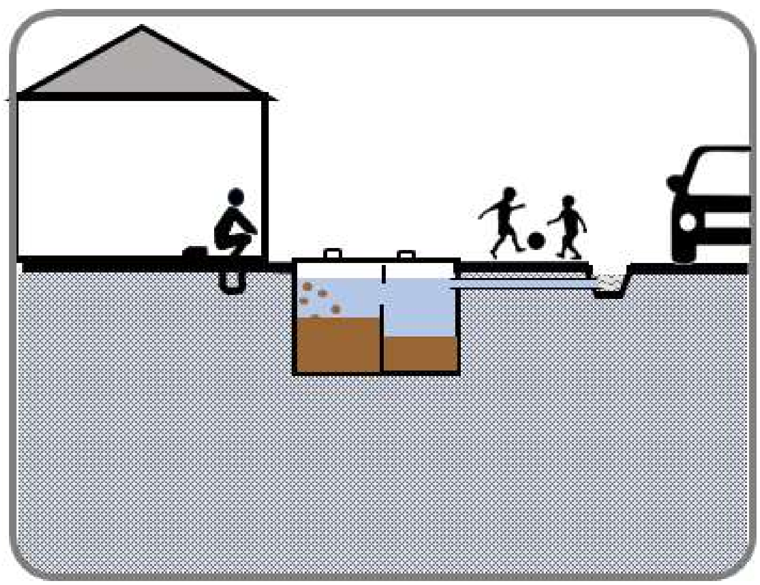
https://doi.org/10.1371/journal.pwat.0000325



PLOS WATER

RESEARCH ARTICLE

Unsafe containment: Public health risks of septic tanks discharging to drains in Dhaka Bangladesh

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Abstract

Sanitation approaches in low-income urban areas are predominately on-site sanitation, with septic tanks promoted as an improved sanitation solution. While a septic tank system is designed to contain sludge in the tank and discharge effluent to a soil infiltration system, in many urban contexts effluent from tanks discharge directly to open drains or surface waters. This research addresses the paucity of data on pathogen removal and discharge from septic tanks as operated in low-income contexts and the significance of this public health hazard. This study assessed the performance and risks of "septic tanks" discharging to open drains in a low-income neighbourhood in Dhaka, Bangladesh, considering the influence of usage and tank operation on concentrations of Norovirus GII, *Salmonella* Typhi, *Vibrio cholerae*, *Giardia*, *Shigella* and *E. coli* in the effluent and receiving drains. While 66% of septic tanks were functioning within design limits, multiple pathogens were detected in all effluent samples, with a mean concentration of 7.6 $\log_{10}$ MPN/100mL for *E. coli* and 4.2–5.6 $\log_{10}$ genome copies/100mL for pathogens, excluding *S.* Typhi which was not detected. Children's exposure to septic tank discharge in drains could result in an 18% risk of illness from Norovirus GII and 3% from *Giardia* annually. The pathogen reduction between the estimated septic tank inflows and measured effluent concentration ranged from 1.3 $\log_{10}$ MPN reduction for *E. coli* to 2.2 $\log_{10}$ genome copies reduction for *Giardia*. Increased coverage of septic tanks was significantly associated with reduced concentrations of *Shigella* in open drains compared to direct discharge from toilets, with increased reduction for septic tanks operating within design standards. Implementing septic tanks without sub-surface infiltration or treatment of effluent is a major concern. The potential health risk of exposure to septic tank effluent warrants increased attention to appropriate technical design, effluent management and alternatives such as networked sanitation.

Competing interests: All authors declare no competing interests (financial or non-financial), however Timothy Foster is listed on the editorial board for this journal.

Introduction

Septic tanks are used by 2.1 billion people globally [1]. Between 2000 and 2022, six times as many households gained a septic tank compared to households gaining a new sewer connection [1]. Septic tank systems are promoted as an improved sanitation solution in urban and rural areas, particularly when sewers are unavailable. The citywide inclusive sanitation approach promotes on-site sanitation as part of a mix of technical solutions for urban areas [2]. However, many 'septic tank systems' do not comply with technical standards. A standard septic tank system consists of a two-chamber baffled tank for settling and storing sludge and a subsurface infiltration system (i.e. soak pit or leach field) for effluent treatment and disposal [3]. The tank only provides primary treatment and further effluent treatment, particularly to reduce microorganisms, is achieved through filtration and absorption in unsaturated soil [3, 4]. However, recent data indicates many so-called "septic tanks" lack the critical soil infiltration step and discharge directly to surface drains [5, 6]. Little is known about the public health risks associated with septic tanks discharging to drains, and there is limited research on the discharge of pathogens from septic tanks as they are used in low- and middle-income countries.

Global monitoring indicates that septic tanks discharging to the surface environment are prevalent in both low- and high-income countries [7]. Analysis of faecal waste flows in 39 cities in Asia and Africa found that 39% of tanks and pits were connected to open drains or water bodies [5]. In India, a survey of 3000 households in 10 cities found that 72% of septic tanks discharged effluent to drains [8]. In Hanoi, Vietnam, a study of 750 households found that 98% of septic tanks discharge to open channels or old sewer pipes not connected to treatment facilities [9]. National inspections in Ireland found that 9–13% of on-site systems discharge directly to streams and drains [10, 11]. Discharge to the surface is also common in rural United States [12]. These findings are now also reflected in global monitoring of the Sustainable Development Goal (SDG) target 6.2.1 of safely managed sanitation services, which requires that on-site sanitation systems contain excreta so they are not discharged to the surface environment [1]. Where local data are unavailable, estimates for safely managed sanitation are based on the assumption that 50% of septic tanks are not contained.

Contaminated open drains are a critical pathway of human exposure to faecal pathogens in low-income areas. While there are multiple pathways for exposure to pathogens in urban areas, several studies have applied quantitative microbial risk assessments (QMRA) or similar approaches (i.e. the SaniPath method) to compare health risks from different pathways and found that direct exposure to pathogens in open drains or gullies was a greater risk than exposure to contaminated drinking water, soils, and other pathways [13–17]. People in low-income areas, particularly children, are more frequently exposed to open drains and pollutants than in high-income communities [14, 18–21]. Drainage networks transport pathogens across cities; therefore, the entire community, not only the households with inadequate sanitation, are at risk of exposure to untreated excreta discharged to the environment [22]. The human right to sanitation implies that people not only have a right to a hygienic toilet but also have a right not to be negatively affected by poorly managed faecal waste. This point is also emphasised in the UN-adopted human right to a clean, healthy, and sustainable environment [7, 23].

The above studies identified the high levels of contamination and exposure to polluted drains but did not point to the sources of contamination. Various sanitation failures contribute to faecal contamination of drains, such as runoff from open defecation, direct discharge from toilets, on-site sanitation directly connected or overflowing to drains, and sludge dumped locally [5]. Environmental sampling in Ghana found *E. coli* concentrations were lower in, or near, clusters of households with high coverage of sanitation facilities, especially contained facilities [24]. Environment sampling in India and a desk-based model in Uganda found that direct discharge from on-site systems contributed to greater pathogen releases to the environment than dumping of faecal sludge in drains [21, 25]. Furthermore, climate change is predicted to increase the frequency and severity of flooding in many of the same low-income urban areas where septic tanks discharge to drains, likely increasing exposure to contaminated drains [21].

Despite the widespread use of septic tanks, limited data exist on the fate of pathogens in septic effluent and the magnitude of related public health risks [4, 26]. While the impact of pathogens from septic tank effluent has been studied in relation to the groundwater risk from sub-surface infiltration [27–30], few studies have assessed the risks of septic tanks discharging to drains or the environment. A number of studies have investigated pathogen concentrations in dry pit latrines and a recent systematic review of pathogen reduction in on-site systems also only included dry latrines and sludge with no mention of effluent [31–33]. Another recent compilation of data on pathogen reduction within septic tanks only identified two studies with in-situ data from standard two-chamber septic tanks [34, 35], with other data from models, laboratories or advanced on-site treatment systems [36]. Data on pathogen concentrations in septic tank effluent were available from single studies for *Giardia* (twin settling tanks receiving sewer inflows) [37] and *Shigella* (modified septic tank including filter chamber in a laboratory) [38] and from a small number of studies on *E.coli* [11, 39–42].

Many of these studies were conducted in high-income countries, where influent pathogen loads are expected to be lower, and from controlled studies which do not consider that systems in situ may not follow ideal operating conditions. The implication of poor operation has been studied in relation to nutrient releases [9, 43, 44]; however, only two studies, both in India, assessed the influence of septic tank operation on pathogen release. One found a significant reduction in the concentrations of *E. coli* in tank effluent with increased liquid retention time and increased years of use, but no significant association with emptying frequency, sludge depth or user numbers [25]. The other research indicated a reduction in faecal coliforms in drains and rivers over three years following the implementation of regular emptying of septic tanks [45]. There remains a gap in data on the pathogen removal and discharge from standard two-chamber septic tanks discharging to drains in the conditions in which they are implemented and operated in low- and middle-income countries.

Given many so-called "septic tank systems" only include a tank discharging directly to open drains or other surface environments, it is critical to understand the contribution of these tanks to the faecal load and exposure to pathogens in open drains. This research aims to provide insights into the faecal pathogen discharge and risks associated with the current use of "septic tanks" in dense low-income areas. Specifically, the objectives were to: 1) quantify the presence and concentration of different pathogens discharged from identical well-constructed two-chamber tanks; 2) consider the factors that influence operation and treatment performance; and 3) provide insights about the extent to which such systems provide a meaningful public health improvement as compared with direct discharge from toilets to drains.

Methods

Data collection

Ethics statement. The study protocol for this and the broader data collection was approved by the International Centre for Diarrhoeal Diseases Research, Bangladesh (icddr,b) scientific and ethical review committees (protocol number PR-19011, 2019) and also by the University of Technology Sydney (UTS HREC REF NO. ETH18-2599). Icddr,b secured agreement of the community to participate through the community leaders and informed concent was received from all participants in household surveys and compound inspections. Additional information regarding the ethical, cultural, and scientific considerations specific to inclusivity in global research is included in the Supporting Information (S1 Checklist).

Study site and population. The study site of Mirpur, Dhaka, was selected to represent urban areas in low-income countries with high population density, poor quality sanitation services and human exposure to water in open drains. It also had characteristics necessary for the study purpose, including the presence of a mix of sanitation systems, including toilets discharging directly to drains and to septic tanks, and the hydraulic characteristics that ensure that all drain flows were generated (and contaminated) from within the same community without upstream inflows under normal conditions (i.e. only during significant flood events). The study site consisted of four parallel streets (Fig 1), each with a similar arrangement of residents living in clusters of households, typically single rooms, located within compounds. The compound enclosed facilities shared between the residents, including shared toilets, water supply, bathing, cooking, and cleaning areas. The study area included 172 compounds, housing 4,792 people, with an average of 8.5 households per compound and 3.2 people per household (Table 1).

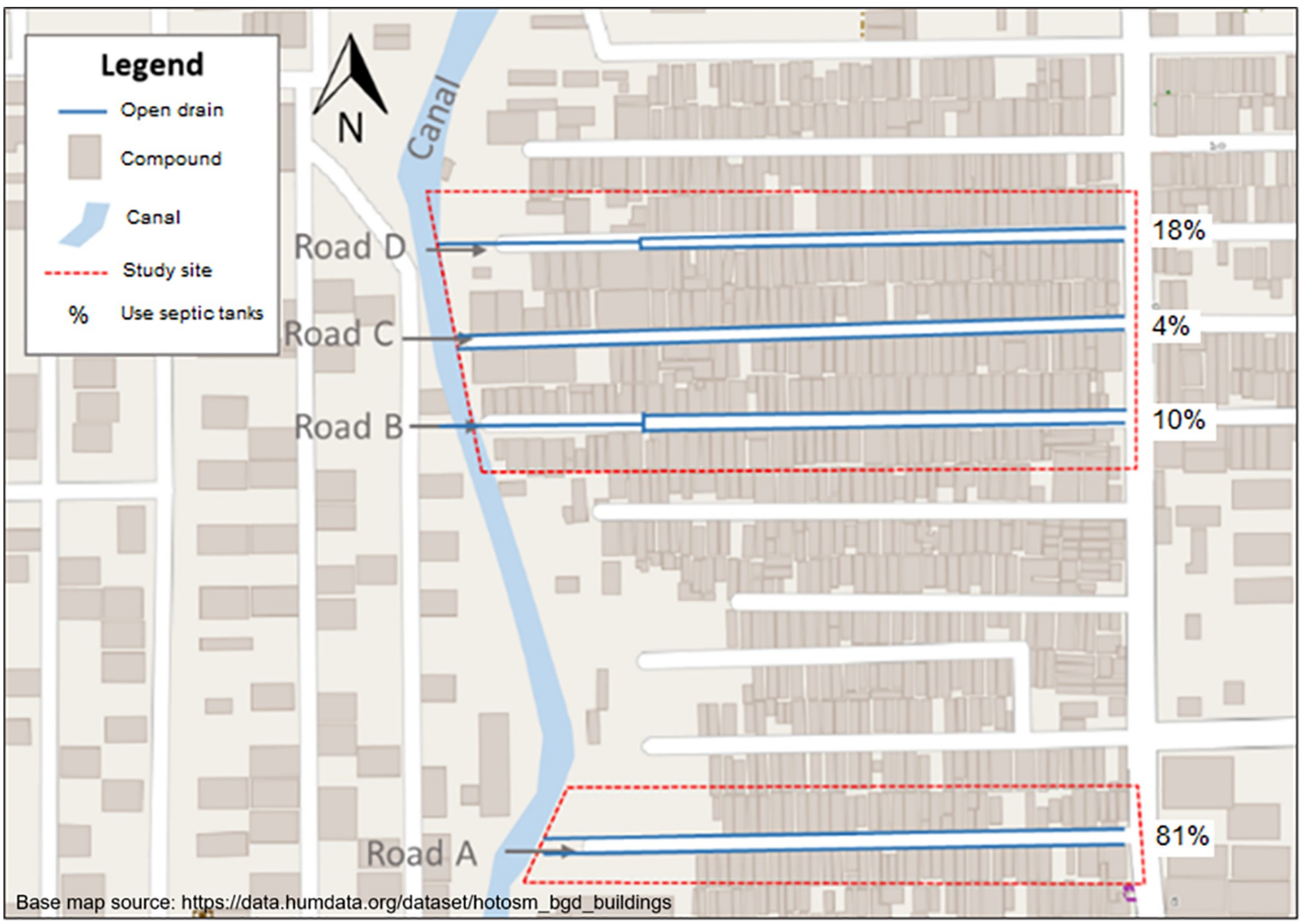

Fig 1. Layout of four roads study site and proportion septic tank use (bounded by dotted red perimeter) (adapted from Foster et al. 2021, source open street map, humanitarian data exchange CCA 4.0).

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Table 1. Summary of site characteristics by road.

Road	Population	Compounds	% population use septic tank	% population use functioning septic tank	Average age of tank
D	1351	51	18%	15%	2.9
C	1277	47	4%	2%	2.2
B	1194	42	10%	13%	1.3
A	970	32	81%	28%	4.8
TOTAL	**4792**	**172**	**24%**	**14%**	**3.4**

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Data collection. This research was part of a broader project that developed new methods for sampling and analysis of pathogens in the environment [46], and produced a model of pathogen flows from sanitation systems to assess improvement options [47]. Data collection relevant to this study included household surveys, infrastructure assessments and environmental sampling, which were conducted by trained research staff. Respondents for the household survey were randomly sampled and included 2–3 households per compound resulting in a sample size of 349 households (30% of the study site population). The survey assessed water and sanitation use and frequency of human exposure to open drains. The infrastructure census captured 96% of the survey area (173 compounds) to assess all inflows into the open drain through observation of the sanitation facilities, water meter and drain, and included a survey for each compound to establish the number of users per sanitation facility, emptying practices, and frequency of flooding. The survey and census were conducted the 7–26 May 2019 and 16–22 April 2019, respectively, in Bangla with adult respondents only and formal informed verbal consent provided and recorded, with all data recorded using DoForms, a mobile-based data collection platform.

Environmental sampling was conducted to estimate pathogen concentrations in septic tank effluent and open drains. Faecal pathogen and faecal indicator bacteria (FIB) concentrations were measured from grab samples from the septic tank effluent (n = 18 and four repeats) and at the mid and end point locations of drains in each street (n = 33) in wet and dry seasons. Quantitative polymerase chain reaction (qPCR) was used to detect and measure the concentration of Norovirus GII, *Salmonella* Typhi, *Vibrio cholerae*, *Giardia* and *Shigella*. The concentration is expressed as $\log_{10}$ EGC per 100mL, with the equivalent genome copies (EGC) estimated in each sample by interpolation of the mean Ct value (averaged from duplicate wells) to the standard curve and the concentration calculated using the dilution factor for each sample type. For quality assurance, one sample processing negative control was included for every 10 samples and one pathogen specific positive control and one negative control (molecular water) were included in each real-time PCR plate (See Liu 2021 for further details) [48]. The IDEXX-Quanti-tray 2000 technique with Colilert-24 media (IDEXX Laboratories, Westbrook, Seattle, WA) was used to quantify the most probable number (MPN) of *E. coli* per 100 mL of liquid sample. The estimation method from the U.S. Food and Drug Administration's Bacteriological Analytical Manual (BAM) was adapted to determine the E. coli concentration in the test sample from the combined result of the three dilutions, resulting in a single MPN estimate with 95% confidence limits [49]. The environmental sampling technique and laboratory methods for sample analysis are presented in Amin et al. [46]. These pathogens were chosen due to their reported prevalence of disease in Dhaka [50–54], pre-testing using TaqMan to identify priority pathogens and the availability of sensitive and specific methods for detection in environmental samples (see Foster et al.) [47]. Sludge depths were measured in seven tanks that could feasibly be opened, with samples taken from both chambers using a core sampling device (i.e. sludge checker) which allowed measurement of the depth of sludge and supernatant [55].

Analysis of data

Assessment of septic tank operation. Septic tank operation was assessed based on two widely accepted criteria for septic tank design: the hydraulic retention time (HRT) and the accumulated sludge volume at emptying [56]. Common national design standards suggest tank sizing should be based on maintaining 24-hour minimum design HRT when the tank is around two-thirds full of sludge and ready for emptying [56–59]. For this analysis, a septic tank operating within design standards was defined as having at least 24 hours HRT and less than two-thirds sludge volume. The sludge accumulation rate was calculated using data from complete sludge depth samples for six individual sample systems with the reported number of users and years of operation from the census. The resultant average sludge accumulation rate (28.8L/p/year) was used to estimate sludge volume in the remaining systems (see Tables C and D in S1 Appendix). The HRT was calculated from the reported percentage water used for flushing (6%), median daily water-use from meter readings and water bills (196 L/p/d), the sludge volume and tank hydraulic volume (5.3m^3) from the construction drawings provided by the organisation that managed the construction.

Analysis of septic tank effluent and pathogen reduction. Analysis of effluent samples was in IBM SPSS v28. Firstly, we analysed the variability of repeat effluent measurements which were collected two months apart for four tanks, with the second measurement included in analysis. The relative difference between repeats was calculated for repeats with pathogens present in both samples (n = 10 pairs). Next, the association between septic tank operation parameters and the concentration of positive samples of pathogens and *E. coli* in effluent were assessed using Pearson's correlation coefficients with a state of significance of <0.05. The operational parameters considered were (i) years of operation, (ii) reported numbers of users, (iii) whether sampling occurred in the wet or dry season, (iv) HRT, (v) estimated sludge depth, and (vi) sludge volume as a proportion of total volume (expressed as a binary, with a positive value if sludge volume was less than two-thirds full, i.e. operating within design standards). Lastly, generalised estimating equations (GEEs) were used to analyse the association between the mean concentration in positive drain samples and the population using septic tanks connected to that drain, looking at both general septic tank use and the population using septic tanks operating within design standards. The analysis adjusted for season as an explanatory variable and road as a within-subject variable.

The log reduction of pathogens in septic tanks was assessed by comparing the measured effluent concentration with an estimated influent concentration (see detailed analysis in Tables F-H in S1 Appendix). It was not feasible to capture a representative sample of inflow, so the influent concentrations for Norovirus GII, *Giardia* and *E. coli* concentrations were estimated based on reported disease prevalence (literature from Dhaka), burden of disease in Dhaka (local health surveillance data), asymptomatic diarrhoea cases in Dhaka (local data and literature), shedding load (literature), duration of shedding and duration of symptoms (literature), excreta produced (literature) and water volume generated daily per capita (census and questionnaire data). The mean inflow and confidence intervals were estimated from variation in water use (from first to third interquartile range, n = 24) and low and high estimates of prevalence and shedding rates (Tables F-H in S1 Appendix). The influent estimates for Norovirus GII and *E. coli* were equivalent units to the water quality measurements; however, for *Giardia* it was necessary to convert the influent estimate in cysts/100mL to genome copies/100mL, assuming 16 genome copies per cyst [60]. A simple conversion was not possible for *Shigella*, *S.* Typhi or *V. Cholerae;* therefore, influent concentration could not be estimated. The log reduction was calculated as the difference between the mean influent concentrations and the arithmetic mean of the measured concentrations of positive effluent samples.

Analysis of septic tank discharge to drains. To compare the influent and effluent concentrations with reports in the literature, the measured blackwater (toilet only) inflows were converted to a combined (blackwater and greywater) equivalent, as literature was only available for combined flows. The combined water flow was calculated by assuming the greywater flows (91% daily water use from survey data) are mixed with the blackwater flows from toilets (6% daily water use), assuming no pathogens in greywater (see Table B in S1 Appendix [3]). This resulted in a median combined flow of 190L/p/d compared with 12L/p/d for blackwater only, and reduced the concentrations by 1.2 $\log_{10}$ genome copies/100mL (see Tables H and M in S1 Appendix).

To demonstrate the potential health risks of pathogens discharged from septic tanks, we conducted a Quantitative Microbial Risk Assessment (QMRA) to assess the probability of illness that exposure to septic tank effluent in open drains poses to children. The probability of illness was calculated for Norovirus GII and *Giardia* considering drain quality based on three cases: i) a drain with 100% septic tank use (combined discharge of septic tank effluent mixed with greywater to replicate combined flows in drains) ii) a drain with high proportion (81%) of septic tank use (mean concentration of positive samples from the drain in street A), and iii) a drain with a low proportion (4%) of the population using septic tanks (concentration from the drain in street C). The analysis assumed 1mL of water was ingested per drain exposure, which aligned with assumptions used in the Sanipath tool [61], although noting it could be much higher as one study in Dhaka found children ingested 37mL when exposed to flood water [62]. Household survey data indicated that children under five were exposed to drains a median of 14 times per year (from surveys presented by Foster et al. 2021 Fig S3). Given the analysis used the mean positive concentrations yet the pathogens were not present in all samples, the annual exposure frequency was corrected, by multiplying by the occurrence of pathogens in all drain samples (67% Norovirus and 50% Giardia). Dose-response models and probability of illness aligned with the approach described in Foster et al. 2021 [47]. For Norovirus GII we assumed the fractional Poisson dose response model with $P = 0.722$, $\mu = 1106$ and for *Giardia* the exponential model with $k = 5.72 \times 10^{-2}$ [63, 64]. The probability of illness given infection was assumed to be 55% for Norovirus GII and 40% for *Giardia* (Table N in S1 Appendix). Note the measured drain concentration for Giardia in GC/100mL was converted into a cyst/100mL concentration for the dose response model, assuming 16 GC/cyst [60].

Results

Study site and septic tank use

The household survey found all households accessed a piped water supply, including 91% piped into the compound and 9% piped into the house. The infrastructure census on sanitation facilities indicated that compounds typically had one toilet facility (i.e. toilet block) with two pour flush toilets (i.e. cubicles/pans), with each toilet facility used by an average of 21 users from 7 households. Toilets predominately discharge directly to the drain (71%), with others discharging to a two-chamber septic tank (24%), a single tank (3%), a concrete ring pit (1%) or an unknown pit (1%) (Table A in S1 Appendix). All tanks and pits had an outlet pipe for effluent to discharge to the drain, and none discharged to subsurface infiltration systems.

Septic tanks were only present in government-owned compounds and were built through externally funded projects. Prevalence of tanks varied between the four streets: in street A 81% of the population used a septic tank, 10% in street B, 4% in street C and 18% in street D (Table 1). Construction of the tanks occurred in stages therefore the tank ages vary with streets, the oldest in street A (4.9 years) and the most recently built in streets B and C (1.5 years). Tanks were all built to the same design standard with two chambers of 5.3m^3 total capacity for

50 users. Only 2 of the 40 tanks in the study area had been emptied, and both had been operating for 4.9 years. On average, septic tanks were used by 25 people (range 7–52, SD 9.8) and received blackwater (toilet) flows only. Greywater from the kitchen, washing and cleaning discharged to the open concrete-lined drains. The median estimated inflow to the septic tanks was 12 L/p/d, based on the median water use from the compounds with septic tanks (196 L/p/d) and the reported portion of water used for toilet flushing (6% of daily water use) (Table B in S1 Appendix).

In line with design standards, the assessment of operation considered sludge volume and hydraulic retention time (HRT). From the measured sludge depth in both chambers of six tanks, the mean sludge accumulation rate was 29 L/p/year and ranged from 12 to 49 L/p/yr (Table C in S1 Appendix). The average calculated sludge volume of all tanks (n = 40 tanks) was 50% of the hydraulic tank volume, based on the mean sludge accumulation rate, tank dimensions, the reported number of users, and years of operation per tank. The design limit of two-thirds sludge volume was surpassed in 33% (n = 13) of tanks, all located in street A. The average HRT was 14 days (median 8.5 days) and only two tanks exceeded the design criteria of a minimum one-day HRT. For all tanks in the study area, 68% were estimated to operate within the sludge and HRT design (Table D in S1 Appendix). For the tanks from which effluent samples were taken (n = 18), 61% were assessed as operating within design standards.

Pathogen release from septic tanks

All septic tank effluent samples (n = 18) were positive for one or more pathogens and most samples (56%) were positive for two or more pathogens. The highest occurrence was *Shigella*, with 94% effluent samples testing positive, and the lowest was *S*. Typhi, with no positive samples (Table 2). The arithmetic mean concentration of positive samples (excluding non-detects) ranged from 4.2 to 5.6 $\log_{10}$ genome copies (GC)/100mL and 7.6 MPN/100mL for *E. coli*. The variability of pathogen presence in effluent was evident in repeat measurements collected for four tanks two months apart, of which 10 paired samples (of 26 total) were positive in both repeats, with an average 1.0 $\log_{10}$ /100mL or 27% relative difference (Table E in S1 Appendix). The mean estimated influent concentration (considering blackwater only) was 6.4 and 6.7 $\log_{10}$ GC/100mL for *Giardia* and Norovirus GII, respectively, and 8.9 $\log_{10}$ MPN/100mL for *E. coli* (Table H in S1 Appendix). The reduction in pathogens between the mean estimated influent and mean measured effluent ranged from 1.3 $\log_{10}$ MPN for *E. coli* to 2.2 $\log_{10}$ GC for Giardia (Table 2).

Table 2. Pathogen detection and concentration in septic tank effluent samples.

Pathogens	% positive (n = 18)	Unit	Measured effluent concentration[a]			Estimated influent concentration[b]	Log reduction
			Mean	Median	Interquartile Range	Mean (Range)	Mean
Norovirus GII	67	Genome copies / 100mL	4.99	4.54	0.49	6.68 (5.3, 7.2)	1.69
V. *cholerae*	56		4.27	3.20	1.41		
S. Typhi	0		-	-	-		
Giardia	17		4.15	4.21	0.39	6.36 (4.3, 6.9)	2.21
Shigella	94		5.56	2.88	1.49		
FIB (*E. coli)*	100	MPN/ 100mL	7.61	6.56	0.89	8.92 (7.2, 9.5)	1.31

Notes

[a]. Log_{10} transformed arithmetic mean concentration of positive samples.

[b]. Influent concentration and log reduction were only estimated for Norovirus GII, *Giardia* and *E. coli*

[c]. All concentrations are blackwater only.

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The effluent from septic tanks operating within the design standards had a mean concentration 0.92 log_{10} GC/100mL lower than those systems exceeding design standards, although the concentration difference was less for V. *cholerae* (0.03 log_{10}GC/100mL) and higher for *Shigella* (2.9 log_{10}GC/100mL) (Table I in S1 Appendix). The concentration of *Shigella* was significantly associated ($p < 0.05$) with well-operating septic tanks ($r = -0.647$, $p = 0.01$), user.years ($r = 0.637$, $p = 0.01$), estimated percentage sludge volume ($r = 0.635$, p = 0.01) and HRT ($r = -0.647$, p = 0.01) (Table K in S1 Appendix). The concentration of *Giardia* was significantly associated with users ($r = 1.00$, $p = 0.004$) and the concentration of *E. coli* was significantly associated with wet conditions during sampling ($r = 0.522$, $p = 0.03$). No other significant correlation ($p > 0.05$) was detected. Compared with unemptied tanks of a similar age and number of users (4.9 years ago and 35 users, n = 6), the concentration of pathogens in the effluent of the one tank that was previously emptied were 2.1 and 3.4 log_{10} GC/100mL lower for Norovirus GII and *Shigella* and 1.3 log_{10} MPN/100mL lower for *E. coli*, pointing to the potential for emptying to improve effluent quality (Table L in S1 Appendix).

Comparison of toilet and septic tank discharge to drain

The occurence and concentration of pathogens in open drain samples were higher than from septic tank effluent, as most toilets in the study site (71%) discharged directly to drains without any containment. The presence of pathogens measured in samples from open drains (n = 30) ranged from 27% positive for *S*. Typhi to 100% positive for *V. cholerae* and *Shigella*, and half of all samples were positive for at least four pathogens (Table M in S1 Appendix). Drains received a mix of blackwater from toilets and septic tank effluent, and greywater from kitchen, washing, etc. To compare the septic tank effluent concentrations, an equivalent wastewater discharge from compounds with septic tanks was calculated based on the total wastewater flows (190 L/p/d), rather than the blackwater only flows (12 L/p/d). This dilution with greywater reduced the septic tank effluent pathogen concentration by 1.21 log_{10}/100mL for all pathogens. The drain concentration was 1.2 to 2.7 log_{10} GC/100mL higher than the combined flow discharge from compounds with septic tanks (Fig 2 and Table M in S1 Appendix).

To demonstrate the potential health-related impact of the discharge from septic tanks to open drains, the potential risk of illness was estimated using QMRA found that septic tank discharge (considering the concentration of septic tank effluent diluted with greywater) could result in illness of 1,800 and 300 children per 10,000 per year from Norovirus GII and *Giardia* respectively, assuming 1mL of drain water is ingested by children up to 14 times per year (Table O in S1 Appendix).

Analysis using Generalized Estimating Equations (GEEs) found a 10% increase in the population using septic tanks was significantly correlated ($p < 0.05$) with a 0.10 log_{10} GC/100mL reduction in *Shigella*, while a 10% increase in the use of septic tanks operating within design standards was associated with a 0.34 log_{10} GC/100mL reduction in *Shigella* (Table 3). Wet season was significantly associated with an increase in the concentration of *E. coli*.

Discussion

Septic tanks in Dhaka were found to discharge multiple pathogens in high concentrations into open drains. Well operating systems, less sludge, higher HRT and previous emptying were associated with lower concentrations of pathogens in effluent. Although septic tanks provided some reduction in pathogens and *E. coli* concentrations, and their use was associated with lower concentrations of pathogens in open drains than direct toilet discharge, nonetheless, septic tanks discharging to drains pose a major health risk. This section summarises how these

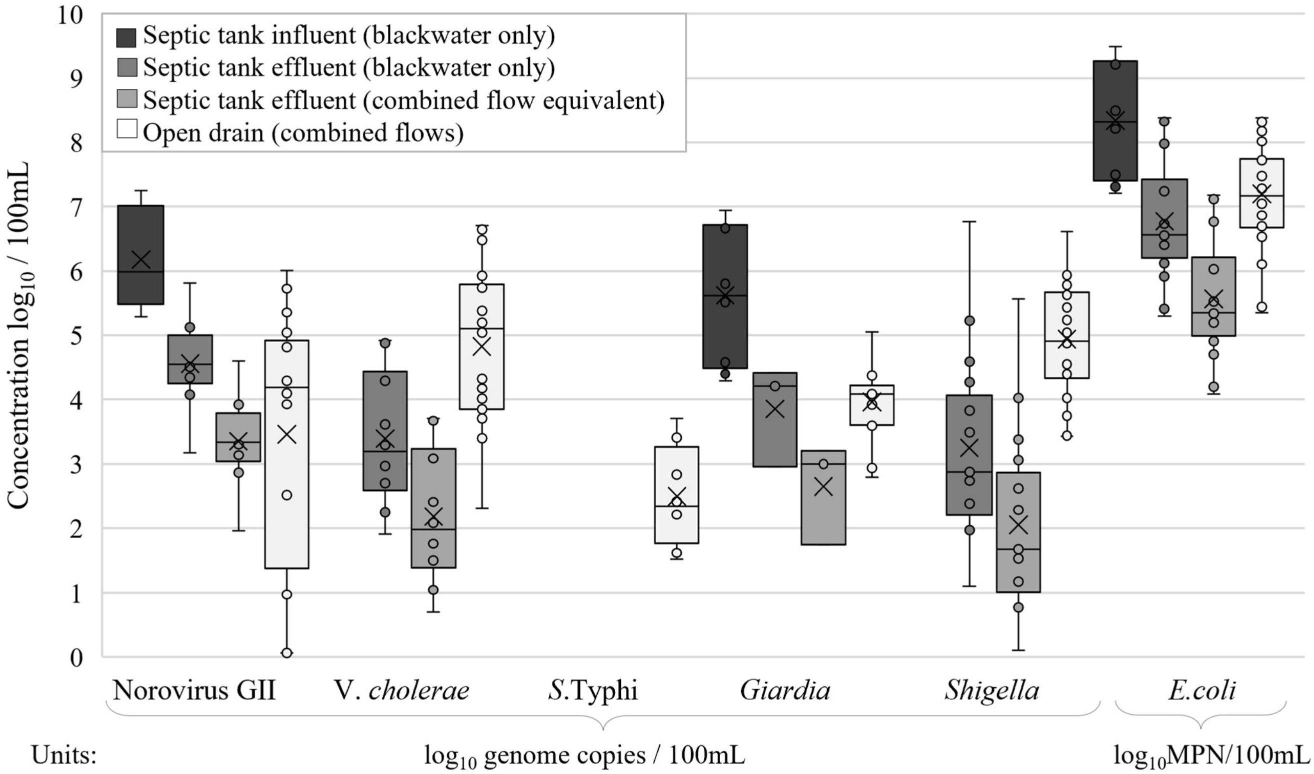

Fig 2. Comparison of pathogen concentrations in septic tank influent (estimated), septic tank effluent (measured blackwater n = 18), septic tank and greywater combined discharge (estimated wastewater equivalent n = 18) and open drains (measured, n = 30) excluding non-detects with error bars indicating the range of concentrations.

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Table 3. Effect of increased septic tank use (typical and well operating) on pathogen concentration in drains, adjusting for season and auto-correlation between samples from the same street.

		All septic tanks		Septic tanks operating within design standards	
		Coefficient (95% CI)	Sig.	Coefficient (95% CI)	Sig.
Norovirus GII	10% increase in use of septic tanks	-0.012 (-0.36,0.34)	0.945	0.22 (-0.85,1.29)	0.688
	Wet Season = 1	0.379 (-1.61, 2.37)	0.709	0.536 (-1.4,2.47)	0.588
V. *Cholerae*	10% increase in use of septic tanks	0.022 (-0.12, 0.08)	0.657	-0.035 (-0.37,0.3)	0.837
	Wet Season = 1	0.452 (-0.31,1.21)	0.244	0.442 (-0.32,1.2)	0.256
Shigella	10% increase in use of septic tanks	-0.099 (-0.19,-0.01)	0.029*	-0.335 (-0.61,-0.06)	0.018*
	Wet Season = 1	0.53 (-0.03, 1.09)	0.062	0.526 (-0.02,1.08)	0.061
S. Typhi	10% increase in use of septic tanks	0.069 (-0.01,0.15)	0.097	0.378 (-0.02,0.78)	0.062
	Wet Season = 1	0.047 (-1.41,1.5)	0.949	0.128 (-1.35,1.61)	0.865
Giardia	10% increase in use of septic tanks	-0.024 (-0.07,0.02)	0.327	-0.026 (-0.22,0.27)	0.839
	Wet Season = 1	0.544 (-0.07,1.16)	0.081	0.53 (-0.08, 1.14)	0.087
E. coli	10% increase in use of septic tanks	0.032 (-0.02,0.09)	0.255	0.131 (-0.06,0.32)	0.180
	Wet Season = 1	0.961 (0.56, 1.36)	0.000*	0.969 (0.57, 1.36)	0.000*

Note

* indicates a significant association (p-value < 0.05 using Wald Chi-square test) between a 10% increase in the population using septic tanks, or a 10% increase in the population using septic tanks operating within design standards and change in the $\log_{10}$ concentration of pathogens in drain samples (n = 30) considering positive samples only and adjusting for season. CI is the 95% confidence interval of the coefficient.

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results compare to the limited available literature on septic tank effluent concentrations, pathogen reductions in standard septic tanks, and concentrations of pathogens in drains. We discuss the high potential risk of illness from septic tank discharge, the difference in pathogen groups and the value of monitoring pathogens, as well as the limitations of this study. Lastly, we reflect on the possible factors influencing the implementation of septic tanks discharging to drains and call for further research to address remaining uncertainties and identify solutions to address this urgent issue facing many low- and middle-income urban areas.

Septic tanks in Dhaka discharged multiple pathogens to open drains with high concentrations that were at the upper end of the limited existing data. Multiple pathogens were present in all effluent samples with a mean concentration ranging from 4.2 $\log_{10}$ GC/100mL for *Giardia* to 5.6 $\log_{10}$ GC/100mL for *Shigella*, and 7.6 $\log_{10}$ MPN/100mL for *E. coli*. Compared to other studies on septic tank effluent, one study in India also monitored effluent from standard septic tanks that received only blackwater and found slightly lower *E.coli* discharge concentrations from private and communal septic tanks that were regularly emptied (6.0–6.9 $\log_{10}$ MPN/100mL) [25]. As the other in-field studies of effluent from standard septic tanks were systems that received combined blackwater and greywater (i.e. kitchen, bathing) inflows, for comparison, the effluent concentrations from this study were converted to an equivalent combined flow based on the estimated greywater volumes (Table B in S1 Appendix). The resultant combined *E.coli* concentration (6.4 $\log_{10}$ MPN/100mL) aligned with the range of effluent concentrations from five studies of standard septic tanks receiving direct household inflows (4.9–7.15 $\log_{10}$ MPN/100mL) [11, 39–42]. The equivalent combined flow of *Giardia* (1.7 $\log_{10}$ cysts/100mL) was lower than the one study from USA on effluent from settling tanks receiving wastewater flows (2.6 $\log_{10}$ cysts/100mL) [37]. Data available on the concentration of *Shigella* in the effluent from a modified septic tank in India (2.1 $\log_{10}$ CFU/100mL) [38] cannot be directly compared to genome copy units of effluent samples. No literature was found for Norovirus GII, *S*. Typhi, or V. *cholerae* concentrations in septic tank effluent.

Septic tanks classified as "operating within design standards", based on measured sludge depth and HRT, performed better than tanks not operating within standards. The assessment of septic tank operation against design criteria found 33% of septic tanks had estimated sludge volumes greater than the design limit of two-thirds full, with only two tanks previously emptied. Overall, the pathogen concentration in effluent samples was 1.0 $\log_{10}$ GC/100mL lower for septic tanks operating within design standards than those beyond standards, although only *Shigella* effluent concentrations were found to be significantly associated with users years, sludge depth, HRT and the overall indicator of functioning. This result aligned with a study of septic tank effluent in India that found a reduction in *E. coli* concentrations with increased liquid retention time, but differed with respect to their finding that an increase in *E. coli* was significantly associated with increased years of use but not with emptying frequency, sludge depth or user numbers [25]. The one sampled tank previously emptied had 1.3, 2.1 and 3.4 $\log_{10}$ lower concentrations for *E. coli*, Norovirus GII and *Shigella*, respectively, than unemptied tanks of the same age, again indicating that less sludge is associated with better quality effluent. The use of septic tanks operating within standards was associated with a three times greater reduction in the concentration of *Shigella* in open drains than use of any septic tanks, yet both were an improvement on direct discharge without storage.

There are very few studies on the removal of specific pathogens by septic tanks in the absence of soil based treatment. The estimated reduction in *E. coli* (1.3 $\log_{10}$ MPN) was within the range reported in studies of in-situ standard septic tanks receiving household flows from Jordan and the USA (0.4 to 2.0 $\log_{10}$ MPN) [41, 65, 66]. The estimated reduction in *Giardia* (1.0 $\log_{10}$ cyst) was higher than found in twin tanks in the USA (0.24 $\log_{10}$ cyst) [37]. Data for *Norovirus GII* reduction was not available for septic tanks but the findings (1.7 $\log_{10}$ GC) were similar to available data from waste stabilisation ponds in Ghana and USA (1–1.6 $\log_{10}$ GC) [67, 68]. A recent compilation of literature on pathogen removal suggested a much higher log reduction of 4–8 in septic tanks, however, the majority of the data reported in that review were from lab-based studies or more advanced on-site treatment such as package anaerobic filters, MBRs and modified septic tanks, which are expected to have higher removal rates [36].

While septic tanks discharging to drains provided some reduction in pathogens as compared with direct discharge from toilets to drains, the high occurrence and concentration of pathogens released to the environment is concerning. The health risk assessment illustrated that given the high likelihood of exposure to open drains in Dhaka, particularly by children, septic tank effluent released to drains is likely to contribute to multiple illnesses per year. Although it was not possible to calculate the risk of illness, the high occurrence and discharge concentration of V. *cholerae* is particularly concerning given drains are a principal transmission pathway for frequent Cholera outbreaks in Dhaka [62]. While septic tanks were promoted as an upgrade on direct discharge, they continue to create a public health risk, hence, the value of this investment is questionable. Other studies have shown that alternative sanitation solutions could be implemented to reduce health risk. For instance, a pathogen flow systems model comparing improvement options for this neighbourhood identified that piping the septic tank effluent to secondary treatment or shifting to centralised sewerage with off-site treatment would achieve the greatest improvement in terms of local exposure [47].

Monitoring pathogens rather than *E. coli* alone is valuable to understand the health risks posed by septic tank effluent. While septic tank performance is often generalised as "pathogen removal", bacteria, viruses, and protozoa respond differently to environmental conditions and within these groups pathogens vary in infectivity, virulence, and persistence [69–71]. The results align with the expectation that removal of protozoa by sedimentation in septic tanks would be greater than for bacteria and viruses [72]. However, given the low occurrence of Giardia in effluent samples (17%) and the small sample, the difference in removal between pathogen groups requires further validation. Further research would also be valuable to compare the reduction in *E. coli* with other pathogens, given indicators, such as *E. coli*, have been found to not correlate well with pathogens released from on-site sanitation [70, 71, 73, 74]. In some conditions, bacterial pathogens (particularly *E. coli*) can increase between the influent and effluent due to regrowth [36, 73].

Our results indicating poor removal of pathogens in septic tanks is not unexpected, yet this prompts the question of why numerous tanks continue to be built without adequate effluent treatment. One common physical restraint is unfavourable soil conditions for infiltration, which was reported as a reason for direct discharge occurring in Dhaka [75]. Another study in the USA reported that 32% of land areas had unsuitable soil for septic tanks, yet they were built anyway due to a lack of public sewer systems [76]. Inadequate financial resources or space and creating an overflow intentionally to reduce the need for desludging are other possible reasons why septic tanks are installed without leach fields or soak pits. Given that so-called "on-site systems" continue to be built in unsuitable soil conditions, it is possible that the health risks of septic tank effluent are not well understood due to the reported low knowledge on pathogens by many sanitation service providers or environmental health authorities [70]. Low awareness of the need to manage effluent from on-site systems may also be exacerbated by the omission of effluent management (i.e. leach field or soak pits) from most on-site sanitation service chain diagrams [77–80]. The ambiguity of containment terminology also doesn't help, with a variety of wet cesspools, pits, sealed and unsealed tanks without effluent management often classified as "septic tanks" [5, 81]. Literature in high-income countries more often refers to "septic tank system" or "septic tank and soak-away system" [11, 44, 82]. We suggest that the language used for a range of types of tanks with and without soil infiltration systems is in need for review [81].

While this paper provides important new data on and analysis of pathogens in septic tank effluent, we recognise a number of limitations of this study. Due to the difficulty collecting influent samples from septic tanks connected underground to toilets, the analysis relied on estimating pathogen concentrations in the influent. This approach is based on multiple assumptions and does not capture the temporal and spatial variability of enteric infections in the user population or shedding by asymptomatic infections, although extended sampling would also be necessary to capture this variability [14, 36]. However, the estimated combined flow inflows aligned with wastewater concentrations in literature, with concentrations of Norovirus GII mid-range and *Giardia* and *E. coli* estimates at the upper end of concentrations in literature (Table H in S1 Appendix). Increasing the number of samples may have provided more information about variability in pathogen occurrence and concentration in effluent from a wider range of septic tanks with different characteristics. However, our analyses were limited due to the cost of analysing effluent samples for pathogens. This will likely also be a constraint for future research, along with the technical capacity and equipment for PCR analysis for pathogen detection in environmental samples, which is not available in all low-income countries. The findings are also expected to be influenced by inherent variations in field conditions and user populations, such as pathogen prevalence, nature of inflows to each tank and possible ingress of flood water. Further research could inform the extent to which septic tank effluent and pathogen removal are influenced by varied pathogen occurrence and concentration in inflows by assessing different populations and larger sample sizes. Lastly, while the data was collected 5 years ago, the situation in Dhaka has not changed and the majority of hosueholds continue to use on-site sanitation or direct discharge, with a large wastewater project only expected to increase sewer connections by 50,000 (0.2% the city population) [83]. Despite these limitations the general finding stands that there is significant flow of pathogens into open drains in dense urban areas which use so-called septic tanks without suitable soil-based treatment and that this is likely to introduce significant health risks.

As septic tanks are often promoted as an improved sanitation solution, the intentional or inadvertent exclusion of the vital soil infiltration treatment step means that these systems may provide a false sense of security, as the tank alone provides minimal health risk reduction compared with direct discharge from toilets. This study raises questions on the value and benefit of continuing to install septic tanks discharging to drains in contexts similar to Dhaka and how to reduce the public health hazard of those that already exist. We call for further research to understand these risks in other contexts and to further investigate the potential for management practices or retrofits (e.g. effluent filters, treatment add-ons, covering drains) to mitigate the significant health risks of existing tanks. More attention is needed to identify and test solutions for septic tank effluent management in dense urban areas where soil, groundwater or density are unsuitable conditions for sub-surface infiltration, and to include these costs when assessing options. To achieve SDG target 6.2 and achieve ongoing health benefits of sanitation many low- and middle-income countries must prioritise safe management of effluent from on-site sanitation, particularly in dense urban areas.

Supporting information

S1 Appendix. Supplementary information.
(DOCX)

S1 Checklist. Inclusivity in global research.
(PDF)

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5. Paper 3

Evidence to inform onsite well and sanitation siting criteria: Risk factors associated with well contamination in urban Indonesia

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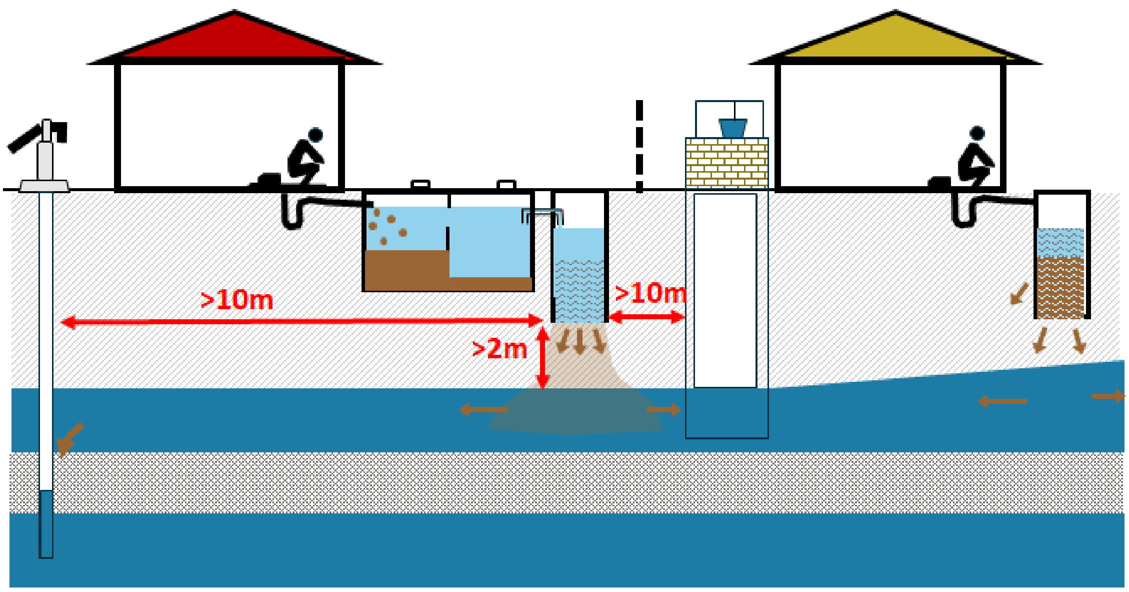

Evidence to inform onsite well and sanitation siting criteria: Risk factors associated with well contamination in urban Indonesia

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ABSTRACT

In Indonesia and many urban areas, the coexistence of on-site sanitation and groundwater supply poses faecal contamination risks. Indonesian standards recommend a minimum 10-meter horizontal separation and 2-meter groundwater depth for siting sanitation systems. This study evaluated the effectiveness of these criteria by mapping wells and sanitation systems in Metro City, controlling for risk factors, and conducting repeated measurements of groundwater depth and well contamination. *E. coli* was detected at least once in 70% of wells, with 36% exceeding 100MPN/100ml. Although 60% of wells were within 10m of a sanitation system, horizontal separation alone was not significantly associated with contamination. Shallower groundwater depths were significantly associated with an increased presence and high concentrations of *E. coli*. However, the 2m threshold was significantly associated with high contamination but not with *E. coli* presence. Water quality and groundwater depths varied over the two-month dry season sampling period, and risk factors varied between the repeat samples and single sample analyses. Other risk factors beyond sanitation also played a role, including uncovered wells, presence of livestock and rainfall. The findings highlight the limitations of standardised

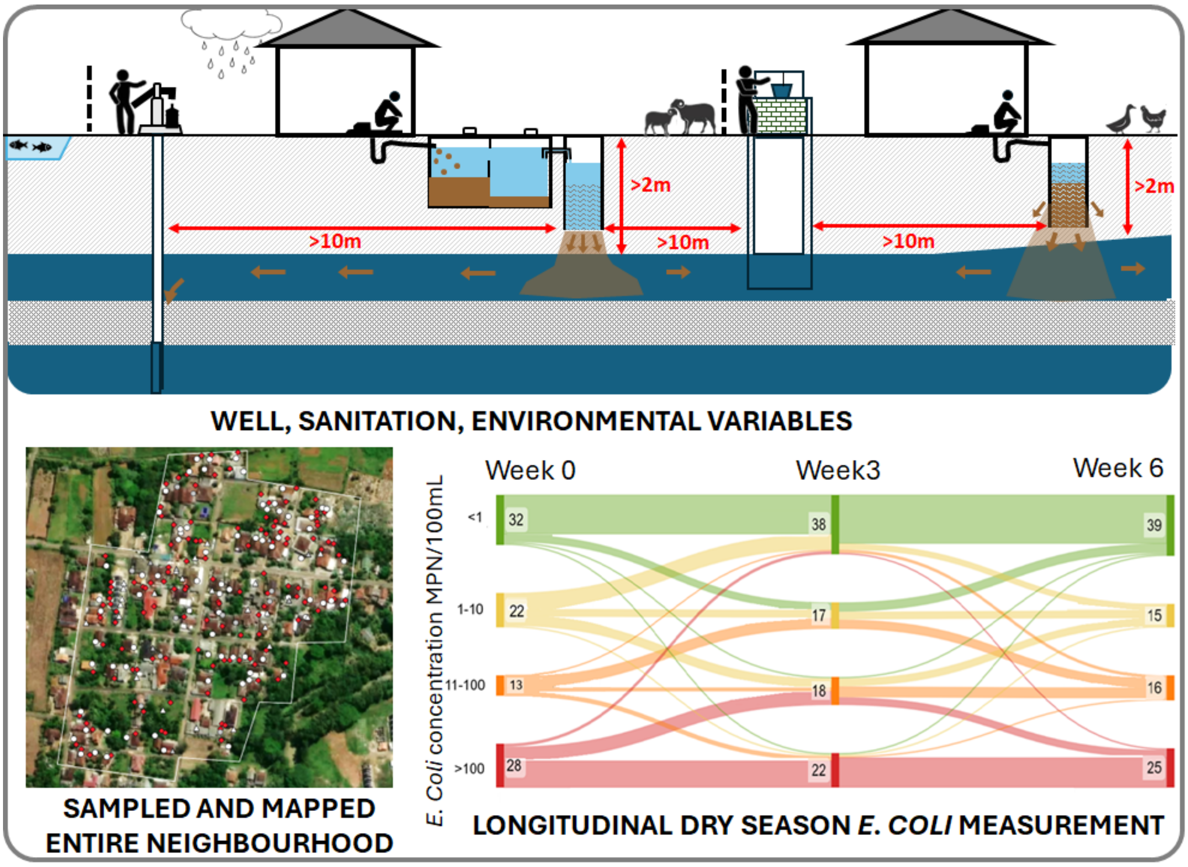
siting criteria, suggesting that site-specific risk assessments may be more effective in managing water and sanitation risks.

Keywords: groundwater contamination, on-site sanitation, risk assessment, sanitation siting criteria, well water quality.

HIGHLIGHTS

- Shallow groundwater was significantly associated with high *E. coli* contamination, controlling for rainfall, underscoring the importance of vertical separation but questioning the effectiveness of the 2m threshold.
- The 10m horizontal separation criterion was not significantly associated with well contamination.
- Repeat sampling is valuable to account for quality and groundwater depth variability.
- Local risk assessments are preferable to standardised siting criteria.

GRAPHICAL ABSTRACT



INTRODUCTION

Groundwater supplies approximately half of the global water for domestic use, which is predicted to increase with climate change (UN Water, 2022). However, the faecal contamination of groundwater is a major issue, contributing to millions of cases of gastrointestinal illness annually (Genter et al., 2021; Murphy et al., 2017; Santos et al., 2023). Over half of the global population uses on-site sanitation, which is increasing more rapidly than access to sewerage (UNICEF and WHO, 2023). On-site sanitation systems have often been considered a principal cause of well contamination (Graham and Polizzotto, 2013; Murphy et al., 2020), with studies linking increased use with declining water quality (Daniels et al., 2016; Templeton, 2015). However, other research suggests that local factors, such as well design and maintenance, may play a more significant role in contamination, challenging the extent to which on-site sanitation contributes to groundwater contamination (Ravenscroft et al., 2017; Sorensen et al., 2016).

Public health authorities often mandate horizontal spacing criteria (i.e. set-back distances) between sanitation systems and wells to mitigate contamination risks (Graham and Polizzotto, 2013; Nenninger et al., 2023). However, implementing these guidelines is particularly challenging in dense urban areas, and transitioning to piped solutions presents its own economic and logistical barriers (Mitlin et al., 2019). In Indonesia, where improving water and sanitation safety is a national priority, this study explored the effectiveness of compliance with the sanitation siting criteria in improving well water quality in an urban area with shallow groundwater.

Despite the common use of siting criteria globally, research findings about their effectiveness are inconsistent. A review of sanitation siting criteria revealed horizontal separation distances ranged from 10-50m and often applied a “one size fits all approach”, failing to consider site-specific conditions such as soil permeability or groundwater depth (Nenninger et al., 2023). The most widely used guidelines recommend a 15m setback distance, reportedly based on four studies, including two from the 1930s, that observed contamination at distances between 25 and 50 metres. While some studies have found correlations between distance and faecal contamination (Daniels et al., 2016; Islam et al., 2016; Ngasala et al., 2019; Sclar et al., 2016), others report no significant relationship (Graham and Polizzotto, 2013; Howard et al., 2003; Ravenscroft et al., 2017). Graham and Polizzotto (2013) emphasised the importance of empirically testing these guidelines under local conditions, while Nenninger et al. (2023) advocate for using modelling approaches to incorporate site-specific variables and uncertainties.

Beyond the horizontal pathway, multiple factors can influence the transmission of pathogens from on-site sanitation to wells, including vertical separation, sanitation type and system density. The groundwater depth is another critical factor in siting on-site sanitation, yet of the four commonly used guidelines, only Lewis et al. (1982) included vertical separation criteria (Nenninger et al., 2023). Studies have shown that shallow groundwater increases the risk of contamination and horizontal pollutant travel (Caldwell, 1938; Cogger et al., 1988; Islam et al., 2016). Sanitation system density is another potential factor, though it is often assessed without controlling for other variables linked to population density. Research in Malawi found that pit latrine density was positively associated with high *E. coli* contamination, controlling for population density (Hinton et al., 2024), while studies in less densely populated areas reported no such relationship (Back et al., 2018). Additionally, the type of toilet or containment is rarely assessed yet contributes very different hydraulic loads to the soil. For instance, wet pit latrines were found to allow bacteria to travel greater distances compared to dry latrines (Caldwell, 1938), yet many studies do not adequately specify the type of sanitation systems assessed (Nenninger et al., 2023).

Compounding the challenge of evaluating sanitation's role in well contamination are other possible contamination sources, such as localised pathways through poorly designed or maintained wells and broader aquifer pathways (Lawrence and Macdonald, 2001). Review papers have criticised the failure of many studies to adequately control for confounding variables (Lawrence and Macdonald, 2001; Sclar et al., 2016). Various studies found that local factors, particularly well infrastructure, pose greater faecal contamination risks than on-site sanitation systems (Ferrer et al., 2020; Ravenscroft et al., 2017; Sorensen et al., 2016).

Water quality variability further complicates assessments, as single-sample testing may fail to capture seasonal or temporal fluctuations. Seasonal changes can impact water quality, particularly for dug wells, though few studies have investigated variability within the same season (Bain et al., 2014). Research in the USA and Ireland demonstrated that single samples substantially overestimated *E.coli* contamination compared to repeat sampling (Gill et al., 2018; Murphy et al., 2020). Studies that collect repeat samples often average seasonal variations, obscuring the fluctuations (Diaw et al., 2020; Escamilla et al., 2013). In Thailand, biweekly monitoring of wells over a year found significantly greater variability in *E. coli* concentrations for dug wells compared to boreholes, as well as identifying four archetypal contamination responses associated with rainfall and water table fluctuations (Chuah and Ziegler, 2018).

In urban Indonesia, 30% of the population uses wells for drinking water, with usage increasing to 66% for non-drinking water purposes, yet recent monitoring found high rates of faecal contamination (Genter et al., 2022; Priadi et al., 2022). Studies investigating sanitation's impact on well contamination in Indonesia have produced mixed results. High contamination levels (>100 MPN/100mL) have been associated with unimproved sanitation systems located within 10m of wells (Cronin et al., 2017; Genter et al., 2022). Conversely, other studies found no significant association between contamination and proximity to sanitation systems (Indrastuti et al., 2021). Indonesian national guidelines recommend on-site sanitation systems in areas with groundwater depths greater than 2m, low porosity soil (<$5x10^{-4}$m/s), and a population density below 15,000 pp/km2 (Pokja PPAS, 2017). National sanitation regulations also require that septic tanks have at least 10m horizontal separation from wells, and unsealed systems (soak pits) are only used when the depth to groundwater is more than 2m in the rainy season (Ministry of Public Works, 2017).

Given the rapid expansion of on-site sanitation systems in urban areas and the growing evidence of faecal contamination of wells, further research is needed to validate whether stricter enforcement of sanitation siting standards can mitigate contamination risks. This study builds on previous recommendations to improve data collection and analysis methods to examine compliance with Indonesian standards, focusing on horizontal and vertical separation between water-flush on-site sanitation systems and wells in urban areas with shallow groundwater. Using mixed methods, including inspections, mapping and repeat *E. coli* measurements during the dry season, this research aims to assess whether adherence to these criteria is associated with reduced faecal contamination.

METHODS

Study Area

The research was conducted in Kota Metro, a small city in Lampung Province, Sumatra Island, Indonesia, with a population of over 170,000 (BPS Kota Metro, 2024a). Only 5% of residents are connected to piped water, and no centralised sewage system exists (BPS Kota Metro, 2024b). Most households use on-site sanitation and on-premises dug wells (i.e. large diameter wells) and boreholes (i.e. drilled wells). The district of Iringmulyo was chosen due to its high rates of stunting, previous findings of poor water quality (Genter et al., 2022), and the presence of a piped water network (providing a possible future alternative), though most households remain unconnected. The study focused on a single area with relatively homogenous geophysical characteristics to reduce hydrogeological variability's influence on contamination patterns. A census sampling approach was adopted to enable a detailed, localised assessment of a typical locality. The study area covered 8.7 hectares across four adjacent neighbourhoods with relatively uniform housing density (see supplementary material, Figure S1). All 132 properties in this area were included in the sampling. Insights from local government, university staff, and well drillers identified clayey sands as the predominant soil type. Groundwater in Metro City ranges from 1 to 5 metres below the surface, underlain by a clay aquitard at depths of 10-20 metres, with a semi-confined gravel aquifer at greater depths supplying boreholes.

Data collection

A mixed methods approach combined household questionnaires, infrastructure mapping, sanitary inspections, depth measurement, and water quality sampling. All 132 households in the study area were sampled, and a response rate of 85% was achieved (Table S1). Questionnaires, administered in Indonesian by trained enumerators using Survey CTO version 2.71.5, collected data on water supply and sanitation types, usage, and emptying practices. Visual inspections observed features and sanitary risks of wells and sanitation systems, followed by detailed mapping of all used and abandoned wells and sanitation systems onto high-resolution printed maps, later digitised in QGIS version 3.22.10 to calculate horizontal and vertical separation distances.

Groundwater samples were collected from all household wells across three sampling phases between August and September 2022 (dry season). Samples were taken directly at the source, either from taps for pumped systems or buckets from uncovered wells, prior to any household treatment. Samples were transported in sterile Whirl-Pak ® bags at 2-8 degrees C in cooler bags for analysis at the Universitas Muhammadiyah Metro for *E. coli* and Total Coliform using IDEXX Colilert-18 using the IDEXX Quanti-Tray ®/2000. Samples were incubated at 35.5 degrees C for 18-20 hours. *E. coli* cells were enumerated using ultraviolet light and the Most Probable Number (MPN) tables. Water quality analysis methods paralleled those explained in Genter et al. (2022).

Groundwater depth was measured in all accessible dug wells (n=59) after each of the three water quality samples using a weighted measuring tape to determine the depth from the ground surface to the water level. Depths of sanitation systems were measured in 31 accessible systems using a metal rod inserted into openings, such as lids or ventilation pipes, to calculate the depth to the system base. Qualitative data on site geology and hydrogeology were gathered from interviews with local well drillers, environmental and public works officers and university staff.

Analysis

Water quality analysis

Given *E. coli* concentrations were not normally distributed, analysis was based on logistic regression with two binary outcome variables: a) *E. coli* presence (equal or greater than 1 MPN/100mL) and b) high contamination (*E. coli* greater than 100 MPN/100mL). The variation in water quality across the three sample rounds was assessed first through changes in *E. coli* risk categories and graphed as a Sankey diagram (Fig. 1), as well as analysis of the difference in proportions of positive outcomes between sampling rounds using Cochran's Q test with a significance level of $p<0.05$.

Mapping and spatial analysis

All wells and sanitation systems were mapped into QGIS v3.22.10. The depth to groundwater at sanitation systems was calculated as the difference between a surface layer created from the Indonesian National DEM 5m elevation data (Badan Informasi Geospasial, 2018), and a groundwater depth mesh generated from the measured depth to groundwater in 59 dug wells for each sampling round. The depth of sanitation systems was measured for 31 sanitation systems, and the infiltration depth was calculated as the estimated depth to groundwater at the sanitation system minus the containment depth.

Analysis of risk factors

Risk factors for groundwater contamination were based on commonly assessed factors (Genter et al., 2022; Howard, 2002; Kelly et al., 2020) and assessed through data from water and sanitation system inspections, household questionnaires, mapping and measurements. Well-related variables included categorical well type (borehole, covered well, uncovered well), dug well type (covered, uncovered without a bucket, uncovered with bucket), binary variables for cracked/missing slab, absence of headwall, and borehole depth as a continuous variable. Some variables (e.g. soil type and population density) were assessed as constant due to the localised study area.

Environmental variables included binary measures of the presence of livestock, unlined ponds or stagnant water within 10m of wells, and other pollution sources within 20m. Depth to groundwater was analysed as a continuous variable as a binary variable (greater or less than 2m), following Indonesian siting criteria. Groundwater flow direction could not be determined, potentially due to the influence of pumped-dug wells and boreholes. Rainfall data were obtained from a nearby meteorological station (BMKG Stasiun Klimatologi Lampung station 96291, https://dataonline.bmkg.go.id/data_iklim) and categorised into binary variables: heavy rainfall for Phase 2 (51mm rainfall over 7 days prior) and light rainfall for Phases 1 and 3 (9mm and 15mm, respectively).

Sanitation related variables beyond the binary 10m separation distance were assessed to monitor the potential interactions and pathogen flows between sanitation systems and wells. These included factors related to horizontal separation distance, density and sanitation type. Calculation in QGIS determined the presence of one or multiple sanitation systems within 10m of the well, the average distance to the closest sanitation system, the number of sanitation systems within 10m, and the inverse sum of the reciprocal distance of all sanitation systems within 30m (adapted from Back et al., 2018).

Correlation between risk factors was assessed using Pearson’s bivariate correlation in SPSS v28, focusing on significant correlations (2-tailed $p < 0.005$) and real-world variable interactions. Table S4 details these results, highlighting collinearity between well cover and bucket use, livestock and other pollution, and unlined ponds and stagnant water.

Statistical analysis of factors associated with well contamination

Generalised Estimating Equations (GEE) in SPSS v28 were used to assess the association between risk factors and well contamination, accounting for the within-subject correlation of repeat measures. Binary logistic regression with a first-order autoregressive relationship (AR1) correlation matrix evaluated the effects of water, environmental and sanitation factors on the outcome variables (a) *E. coli* presence and (b) high contamination, with ordinal phase number as a within-subject variable. Four base models were developed: (1) combined wells (borehole and dug wells), (2) dug wells only, (3) boreholes only and (4) combined wells, yet analysis of single samples and not repeats. See Table S5 for specific factors included in each base model. Sanitation and groundwater variables were then assessed by including different individual factors within the model. Significance was assessed at $p<0.05$, with Bonferroni corrections for the multiple comparisons of sanitation and groundwater variables. Corrected thresholds were $p<0.013$ for horizontal separation, vertical separation and sanitation type, and for density, it was p<0.08 (three variables for two outcomes)(Perrett and Mundfrom, 2010).

RESULTS

Study area

This section summarises the overarching findings of the household questionnaire and inspection results, including the type of water and sanitation facilities. The study area included 112 households with 428 residents, with 96% of households using groundwater as their primary domestic water source, while all used on-site sanitation systems (Table S1). Shared facilities were common, with 12% of households sharing wells and 4% sharing on-site systems, while 14% had multiple systems (Table S1). Of the 96 wells in use and able to be sampled, 76% were dug wells (shallow/large diameter wells), and 24% were boreholes (drilled wells). Relating to sanitation systems, flush toilets were universally used, with 23% cistern flush and 77% pour-flush. Inspections identified that 75% of on-site systems were cesspools (locally known as "*cubluk*"), while 21% were septic tanks.

Water quality results

E. coli was frequently detected in well water, with contamination levels varying across sampling rounds. On average, 61% of samples tested positive for *E. coli*, ranging from 58% to 66% across sampling rounds, resulting in 70% of wells testing positive at least once. Contamination was more common for dug wells (75% tested positive at least once) compared with boreholes (52%) (Table S2 and Figure S2). Across sampling rounds, 36% of wells had *E. coli* concentrations exceeding 100 MPN/100mL at least once, with most of the highly contaminated samples (95%) coming from dug wells. Water quality of individual wells varied over the two-month monitoring period (Figure 1), with only 43% of wells remaining in the same contamination category across the three sampling phases. Variation in contamination occurred between samples, with eight dug wells and one borehole shifting between *E. coli* absence to high contamination within the three-week period. Despite these variations, Cochran's Q test showed no statistically significant differences in the proportion of samples positive for *E. coli* ($\chi2(2) = 2.583$, $p = 0.275$) or that had high contamination ($\chi2(2) = 2.842$, $p = 0.241$) across the sample rounds.

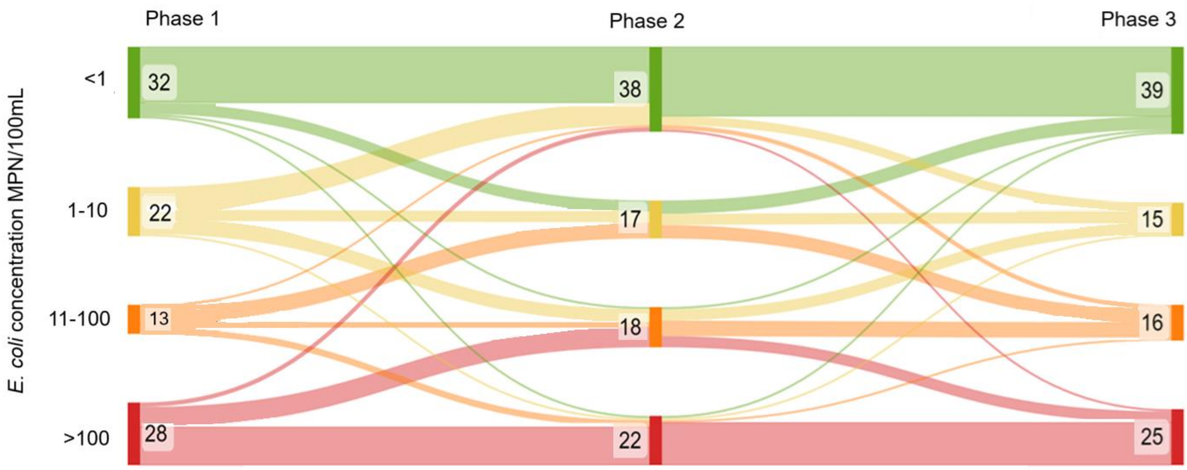


Figure 1: Variations in *E. Coli* concentration categories (MPN/100ml) between sampling rounds (Phase 1,2,3). Green represents the absence of E. coli, and red represents concentrations greater than 100 MPN/100mL.

Risk factors

Compliance with Indonesia’s groundwater depth criteria was high, but adherence to horizontal separation standards was low. Groundwater depth at sanitation systems averaged 2.7-3.14m below ground across sampling periods and ranged from 1 to 5m depths overall (Table 1). Most sanitation systems met the 2m depth to groundwater criterion, with 85%, 78% and 87% compliance rates across the three phases. Repeat measures ANOVA showed significant differences in groundwater depths between rounds ($F(1.85\text{-}175.87)=74.925$, $p<0.001$) based on Huynh-Feldt correction. The average depth of septic tanks (n=31 measured) was 2.04m, ranging from 1m to 3.4m, resulting in an average infiltration depth (from the base of the sanitation system to groundwater) of 0.83m. The range of infiltration depths was -1.87m (base of tank submerged in groundwater) to 2.92m, and 25% of sanitation systems were submerged in Phase 2 when groundwater was shallowest, compared with 11% in Phases 1 and 3. Horizontal separation compliance was poor, as 61% of wells had a sanitation system within 10m, 17% had multiple systems within 10m, and 92% had at least one system within 15m (Table 1). The average separation distance was 9.8m, ranging from 2.9 to 26m. Most sanitation systems were a single wet pit or cesspool (80%), with the remainder classified as septic tanks discharging to soak pits.

Table 1: Summary of factors related to sanitation type, groundwater depth and separation distances

Sanitation variables	n (%)	Horizontal separation variables between well and sanitation system	n (%)
Sanitation type: Septic tank	19 (20%)	Ave. distance well to closest on-site sanitation (SD)	9.6 (SD 4.0)
Sanitation type: Pit	77 (80%)	One sanitation <10m from well	58 (60%)
Toilet type: Cistern flush	18 (19%)	One sanitation <15m from well	88 (92%)
Toilet flush: Pour flush	76 (81%)	More than one sanitation <10m from well	16 (17%)
Previously emptied	12 (13%)	Sanitation density within 30m (inverse sum of the reciprocal distance)	0.40 (SD 0.18)
		Average depth of septic tanks m (SD)	2.04 (SD 0.57)

Depth to groundwater (m) at sanitation system (n=96)			Infiltration depth (m) between base of sanitation system and groundwater (n=28)		
Phase	Average depth (m) (SD)	% >2m	Phase	Average depth (m) (SD)	% >2m
Overall	2.94 (0.79)	83%	Overall	0.83 (0.87)	5%
Phase 1	2.99 (0.76)	85%	Phase 1	0.92 (0.85)	4%
Phase 2	2.70 (0.80)	78%	Phase 2	0.57 (0.87)	7%
Phase 3	3.14 (0.77)	87%	Phase 3	1.01 (0.87)	4%

Multiple other risk factors were also present, including poor well infrastructure, local environmental hazards and rainfall effects. For dug wells (n=73), key risks were the lack of a full cover (80%) and the use of buckets for extraction (25%, Table 2). Boreholes (n=23) had an average reported depth of 40m. Across both types of wells, 17% lacked a protective slab at the base of the well, and 8% had cracked slabs. Of the environmental hazards within 10m of the well, livestock was the most common, followed by other pollution and unlined ponds (e.g. fishponds, greywater storage). The average rainfall 7 days prior to sampling was much higher in Phase 2

(52mm) compared to Phases 1 and 3 (9mm and 15mm, respectively), which corresponded with the shallowest groundwater level.

Table 2: Summary of well and environmental risk factors

Water infrastructure variables	n (%)	**Environmental variables**	n (%)
Well type - Dug well	73 (76%)	Livestock within 10m	41 (43%)
- Borehole	23 (24%)	Other pollution within 10m	26 (38%)
Dug well – uncovered	58 (80%)	Unlined pond within 20m	26 (27%)
Dug well – uses bucket	18 (25%)	Stagnant water near well	15 (16%)
Dug well – no headwall	8 (11%)		
Borehole – reported depth of well	40m (SD 13)	**Rainfall – Previous 7-day rainfall total**	
		- Phase 1	9.0mm
All wells – slab cracked or missing	25 (26%)	- Phase 2	52mm
		- Phase 3	15mm

Variables for the analysis of risk factors accounted for co-dependence and real-world interactions between factors. Significant correlations were found between uncovered wells, bucket use, and lack of a raised wall (Table S3). A combined categorical well variable was created for well type to avoid confounding and included borehole (0), dug well with cover (1), and dug well without cover (2). Regarding environmental factors, livestock presence is correlated with other pollution, unlined ponds, and stagnant water (Table S4), and the correlation is also significant between unlined ponds and stagnant water. Livestock and unlined pond variables were included in the analysis.

Analysis of factors increasing the likelihood of E. coli contamination

The analysis explored associations between sanitation variables and well contamination, and this section presents the results of the combined model, the comparison of separate dug and borehole models, and the comparison between repeat and single sample findings.

Generalised Estimating Equations (GEE) revealed that compliance with the horizontal separation criteria of more than 10m between the well and sanitation system was not significantly associated with reduced contamination risk (Table 3). However, wells with multiple sanitation systems within 10m had an increased likelihood of high contamination levels, although this was not significant after the Bonferroni correction (Table 4). The criteria of groundwater depth greater than 2m was associated with a reduced risk of high contamination (AOR 0.28, p=0.001), but the association with *E. coli* presence was not significant after correction (Table 4). Treating groundwater depth as a continuous variable, as included in the base model in Table 3, showed significant associations with both *E. coli* presence (AOR 0.56) and high contamination (AOR 0.23, p<0.013). Uncovered dug wells were associated with a 7.3 times higher likelihood of *E. coli* presence and a 9.1 times higher likelihood of high contamination than boreholes. Livestock near wells significantly increased the risk of high contamination (AOR 3.9), while sampling during heavy rainfall reduced this likelihood (AOR 0.38).

Recognising different approaches to quantify sanitation proximity and groundwater depth, alternative variables such as distance to the nearest sanitation system, sanitation density, sanitation type, and infiltration depth were also assessed. Aside from the groundwater depth indicators discussed above, this analysis did not find significant associations between alternative sanitation variables and well contamination (Table 4). Multiple sanitation facilities within 10m may be associated with an increased likelihood of high contamination (AOR 3.1, p=0.026), yet was not significant after Bonferroni correction.

Table 3: Adjusted odds ratios of the base model binary logistic analysis using Generalized Estimating Equations comparing the association of base case risk factors with well contamination, considering a) presence of E. coli and b) High contamination (>100 MPN/100mL).

	a) Presence of *E. coli* (>1 MPN/100mL)			b) High contamination (*E. coli* >100 MPN/100mL)		
Parameter	**Adjusted OR**	**95% CI**	***p***	**Adjusted OR**	**95% CI**	***p***
Dug well uncovered (2)	**7.370**	**2.49-21.84**	**0.000**	**9.140**	**1.52-55.09**	**0.016**
Dug well covered (1)	3.295	0.98-11.05	0.053	3.343	0.46-24.33	0.233
Borehole (0)						
Presence of unlined pond	1.069	0.40-2.84	0.893	0.811	0.3-2.18	0.677
Presence of livestock	1.681	0.68-4.13	0.257	**3.872**	**1.43-10.49**	**0.008**
Heavy rainfall phase	0.670	0.44-1.03	0.068	**0.382**	**0.21-0.71**	**0.002**
One sanitation facility within 10m of well	0.755	0.3-1.87	0.544	1.276	0.42-3.87	0.666
Depth to groundwater (m)	**0.559**	**0.36-0.88**	**0.012**	**0.226**	**0.12-0.41**	**0.000**

Note: Bold demonstrates results are significant ($p < 0.05$)

Table 4: Adjusted odds ratios of the association of different sanitation and groundwater variables when added to the base model binary logistic analysis using Generalized Estimating Equations considering a) presence of E. coli and b) high contamination (>100 MPN/100mL).

	>1 MPN/100mL			>100 MPN/100mL		
Parameter [a]	**Adjusted OR**	**95% CI**	***p***	**Adjusted OR**	**95% CI**	***p***
Horizontal distance between sanitation system and well (n=96, *p*<0.013)						
One sanitation facility within 10m of well	0.755	0.3-1.87	0.544	1.276	0.42-3.87	0.666
Distance from well to closest sanitation system (m)	0.977	0.9-1.06	0.575	0.942	0.85-1.04	0.237
Density of sanitation systems around wells (n=96, *p*<0.008)						
Two or more sanitation facilities within 10m of well	2.274	0.76-6.82	0.143	3.098	1.15-8.36	0.026
Count of sanitation facilities within 10m of well	1.174	0.7-1.96	0.538	1.570	0.89-2.78	0.123
Density of sanitation systems within 30m of well	1.680	0.44-6.38	0.446	2.113	0.3-14.74	0.451
Sanitation type (n=96, *p*<0.013)						
Septic tank (not pit latrine)	0.459	0.16-1.32	0.149	0.416	0.11-1.65	0.211
Cistern flush (not pour flush)	0.570	0.19-1.73	0.320	0.716	0.18-2.81	0.632
Groundwater depth (n=96, *p*<0.013)						

Depth to groundwater (m)	**0.559**	**0.36-0.88**	**0.012**	**0.226**	**0.12-0.41**	**0.000**
Groundwater depth >2m	0.561	0.34-0.92	0.021	**0.279**	**0.13-0.6**	**0.001**
Infiltration depth [b] (n=28, *p* <0.013)						
Depth of sanitation system (m)	0.736	0.19-2.84	0.656	NA		
Infiltration depth (m)	0.799	0.33-1.93	0.618	NA		

Notes: a) Each sanitation and groundwater variable is adjusted for Bonferroni correction based on the number of factors assessed and an initial significance of $p<0.05$. The findings in bold are those that are significant. b) The infiltration assessment included one model with depth to sanitation and the standard groundwater depth variable; the other model included infiltration depth (groundwater depth – sanitation depth) and excluded the standard groundwater variable.

Separate models for dug wells and boreholes highlighted differing risk factors, possibly due to variations in contamination pathways and the aquifers they are reported to extract from. For dug wells, there was no significant difference in well contamination for covered, uncovered and uncovered wells using buckets (Table S5). However, heavy rainfall was significantly associated with a reduced likelihood of both *E. coli* presence and high contamination. Increasing infiltration depth was associated with a reduced likelihood of high contamination (AOR 0.140, p=0.014), but this was not significant after correction (p<0.013) (Table S5). In boreholes, missing or cracked slabs were significantly associated with increased E. coli presence, yet groundwater depth, borehole depth, and livestock were not (Table S6).

Analysis of individual sampling rounds highlighted the variability of risk factors and limitations of one-off sampling. Unlike the repeat sample model, single sample models no longer identified uncovered wells as a significant factor for high contamination across all phases, although they remained significantly associated with an increased likelihood of *E. coli* presence compared with boreholes (Table S7). Conversely, the continuous groundwater depth variable was no longer associated with *E. coli* presence across all phases but remained a significant factor for high contamination. The binary groundwater variable (>2m depth) was only significantly associated with high contamination in two of the three phases (Table S7).

While factors such as multiple sanitation facilities within 10m, pit latrines, and higher sanitation density increased the likelihood of high contamination in some phases, these associations were not significant after correction (Table S8). These findings underscore the importance of repeated sampling and comprehensive risk assessments, as contamination pathways and risk factors vary by well type, environmental conditions, and sampling period.

DISCUSSION

This study investigated the associations between sanitation siting criteria and faecal contamination of wells in a densely populated urban neighbourhood in Metro City, Indonesia. By mapping wells and sanitation systems, collecting repeat measurements of well water quality and groundwater depth, and assessing environmental and well-specific risk factors, the findings highlight critical limitations of current horizontal and vertical setback criteria in managing water and sanitation risks.

Indonesian standards recommend a minimum horizontal separation of 10 m between wells and sanitation systems and a depth to groundwater from the surface of more than 2m for safe use of on-site sanitation. While 60% of wells had a sanitation system within 10m and 17% had multiple sanitation systems within this range, horizontal distance alone was not significantly associated with *E. coli* contamination. However, multiple sanitation systems within 10m showed an increased likelihood of high contamination, although this association was not significant after the Bonferroni adjustment. Groundwater depth ranged from 1-5m; only 22% of sanitation systems did not meet the 2m depth to groundwater criteria. Non-compliance with this criterion was significantly associated with an increased likelihood of high *E. coli* concentrations in well water, although not for *E. coli* presence after Bonferroni correction. However, when assessed as a continuous variable, deeper groundwater had a significant association with both a reduced likelihood of *E. coli* presence and a reduced likelihood of high contamination. This suggests that the 2m threshold may have limited effectiveness in reducing the likelihood of contamination. Siting guidance used in other countries focuses on the infiltration depth or separation distance between the base of the sanitation system and groundwater (Lawrence and Macdonald, 2001; Lewis et al., 1982; Nenninger et al., 2023). The average infiltration depth was 0.83m, with all distances less than 5m, which, according to Lawrence and MacDonald (2001), would pose a significant risk of microorganisms reaching groundwater. While infiltration depth was significantly associated with high contamination of dug wells (model 2), it was not significant in other models. However, the analysis was limited due to the small sample size and difficulty accessing and measuring containment depths.

The findings align with studies that report greater contamination risks in shallow groundwater but found mixed results for horizontal separation. Our findings are most comparable to studies in dense urban areas with shallow groundwater. Research in Dar es Salaam found a strong correlation between sanitation proximity and shallow well contamination (Gondwe 2019), while in India 10m was considered an adequate separation distance (Banerjee, 2011) and in Kampala there was no association between latrine presence and contamination (Howard 2003). The increased risk of contamination for shallow groundwater aligns with previous studies (Diaw et al., 2020; Katz et al., 2010; Nenninger et al., 2023). As noted in Mbae et al. (2024), the variability of methods to assess groundwater risk, the factors assessed, and the local contexts complicate comparisons.

Contamination in household wells was also influenced by risk factors associated with the well infrastructure and its use. Uncovered dug wells were associated with a significantly increased risk of *E. coli* presence and high contamination compared with boreholes. No significant difference was found between covered wells and boreholes. Although boreholes showed better water quality than dug wells, 52% still tested positive for *E. coli* in at least one sample. Cracked or missing slabs significantly increased the likelihood of contamination in the borehole-only model. This aligns with previous research highlighting that while boreholes are an improved supply, they do not guarantee water free from contamination (Bain et al., 2014). While the boreholes intercept a semi-confined aquifer, the findings align with studies that indicate poor well infrastructure may allow surface water to enter boreholes (Daniels et al., 2016; Escamilla et al., 2013). These findings suggest that improvements to well infrastructure could reduce risks, particularly by covering wells. While this is already a criterion for the SDG target of improved water supplies, it is not well captured in Indonesian monitoring as a protected well is defined in monitoring systems by the height of the headwall, depth of lining and surrounding slab, but not the presence of a cover (BPS, 2016). Upgrading to boreholes or connecting households to piped supply could mitigate contamination risks, although neither source is guaranteed to be free from contamination, and the population connected to piped water is low in Indonesia (23%) and Metro City (5%) (BPS Kota Metro, 2024b; UNICEF and WHO, 2023).

Local and environmental factors, including livestock presence and rainfall, also influenced well contamination. The presence of livestock near wells was significantly associated with an increased likelihood of high contamination, as has previously been reported in India, Bangladesh and Timor Leste (Odagiri et al., 2016; Wardrop et al., 2018). Interestingly, the heavy rainfall period was associated with a reduced likelihood of high contamination, contrasting with previous studies reporting increased contamination with rainfall (Kostyla et al., 2015; Murphy et al., 2020). In our study, this effect is likely to be due to dilution from rainfall. Our study observed heavy rainfall events in the dry season and controlled for groundwater depth, whereas earlier studies typically compared contamination in wet and dry seasons and did not adjust for groundwater depth. The processes influencing contamination transport are dynamic, with complex interactions between surface infiltration, groundwater flow and rainfall; our findings are associated with rainfall during the dry season, and different associations might be observed in the wet season.

Temporal variability was also evident, with *E. coli* contamination levels and groundwater depth fluctuating between sampling rounds. Comparing the repeat and single sample models highlighted variations in the significance of risk factors associated with well contamination. Groundwater depth showed weaker associations with contamination in the single sample models, and the association of well type and sanitation factors with contamination varied across sample rounds. While the temporal variability in well quality is widely recognised, few studies have collected and analysed repeat samples, and those that do often compare wet and dry seasons, which can present substantially different conditions (Howard et al., 2003; Murphy et al., 2020; Wright et al., 2013). Repeat analysis allows a more nuanced understanding of the dynamic interactions between containment pathways, groundwater and wells. GEE provides population-averaged results, and using repeat measures provides a more robust analysis that accommodates the real-world variations in water quality and the complex effects of groundwater and rainfall interactions, providing insights beyond those achieved with one-off sampling and analysis.

These findings question the effectiveness of a one-size-fits-all approach to sanitation-siting to inform the suitability of on-site sanitation and mitigate risks to groundwater supplies. Horizontal separation from sanitation facilities was not significantly associated with well contamination at this site under the methods applied. While some sanitation density factors showed weak association in some models, groundwater flow direction may increase horizontal transmission in certain directions, yet the direction was inconsistent at this site. While larger separation distances are recommended by some guidelines, they would be impractical in densely populated areas like Metro City, where 98% of wells had a sanitation system within 15m. The adequacy of the 2m depth to groundwater criterion also requires reassessment considering local soil characteristics (Henneman, 2020; Lawrence and Macdonald, 2001). While it may be sufficient in Metro's clayey soils, it may be insufficient in areas with more permeable sandy soils, which are prevalent across Indonesia. Many studies also highlight the influence of depth to groundwater on horizontal travel distance, further adding to the complexity of single setback distances (Nenninger et al., 2023). The simplicity of these separation criteria means that the influence of local conditions on pathogen transport is not adequately considered (Graham and Polizzotto, 2013).

To better manage these risks, water and sanitation safety planning and routine sanitary inspections are promising alternatives (Twinomucunguzi et al., 2020; WHO, 2024a, 2024b). Inspection-based risk assessments could target high-risk areas, such as those with shallow groundwater, poor water quality, or lacking piped supplies, to identify common hazards in well and sanitation systems and inform localised risk management strategies. These approaches could build on existing environmental health risk assessments or be integrated into local inspection programs, such as those conducted by sanitarians as part of national ending open defecation initiatives. While modelling has proven valuable for understanding the complex dynamics of groundwater contamination (Back et al., 2018; Nenninger et al., 2023) scaling modelling assessments in Indonesia would be challenging due to limited local government capacity. Although it could be argued that on-site sanitation and on-premises wells are incompatible in urban areas and piped water systems should be prioritised, the slow expansion of piped connections in Indonesia underscores the ongoing need for solutions to manage the risks associated with on-site systems and wells.

Several methodological and site-specific constraints limited this assessment of sanitation separation criteria on well contamination. The census approach was effective in controlling for many environmental variables; however, an ideal site would have avoided major known contamination risks such as uncovered wells and livestock to prioritise the assessment of sanitation pathways. Dedicated piezometers could provide a clearer picture of the sanitation to groundwater transmission pathway and avoid issues with local well contamination, although building piezometers in built-up residential areas is complex. Similarly, using rainfall gauges, rather than relying on data from the nearby weather station, could provide a more accurate and time-sensitive assessment of rainfall. The inability to differentiate between human and animal sources of faecal contamination limits the specificity of the findings. However, methods to differentiate these sources are often unavailable in small towns such as Metro City. (e.g. Odagiri 2016, Fuhrmeister 2019, etc.). In addition, larger samples would be beneficial, particularly for infiltration depths, given the stricter statistical thresholds required for multiple-hypothesis testing. Lastly, the study's focus on the dry season may not represent the issues in the wet season, given prolonged rainfall and raised groundwater levels may alter contamination pathways.

CONCLUSION

The interactions between on-site sanitation and groundwater supply are complex, and simple separation distances or depth criteria may be insufficient to effectively manage contamination risks. Depth to groundwater was a critical factor, with contamination risks decreasing at greater depths. While the binary 2m depth criterion was associated with reduced high contamination levels in the clayey soils in Metro, it may be inadequate in sandy, more permeable soils, as are common in Indonesia. Horizontal separation of sanitation systems was not significantly associated with well contamination in this study and the findings emphasise the need for a nuanced understanding of the many local factors influencing contamination pathways in urban areas. Building on previous studies, our risk factor assessment was made more robust by the census sampling and repeated measures of water quality and groundwater depth, capturing real-world variability and strengthening the analysis of contamination risks. Given that multiple factors were assessed to reflect the varied contamination pathways, a larger sample could give more explanatory power to this approach. While models provide valuable insights into the complex factors contributing to contamination, it is challenging to scale such assessments. Given compliance with siting criteria alone is likely insufficient to minimise well contamination risks, local risk assessment approaches, such as safety planning or targeted inspections in high-risk areas, are recommended to identify locally relevant hazards and improvement options. While transitioning to piped water, boreholes, or sewer systems may reduce risks, immediate measures are needed to manage the ongoing use of dug wells and on-site sanitation in urban Indonesia. Increasing urbanisation and climate hazards are expected to exacerbate well contamination risks, making localised integrated water and sanitation risk management essential for ensuring safe and sustainable services.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or the Supplementary Information.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

Free and informed consent was obtained from the participants. The study protocol was approved by the UTS Human Research Ethics Committee at the University of Technology Sydney, NSW, Australia, Protocol # UTS HREC ETH20-5620, approved 6 July 2021.

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SUPPLEMENTARY MATERIAL

Supplementary Material attached.

6. Paper 4

Indicators to complement global monitoring of safely managed on-site sanitation to understand health risks

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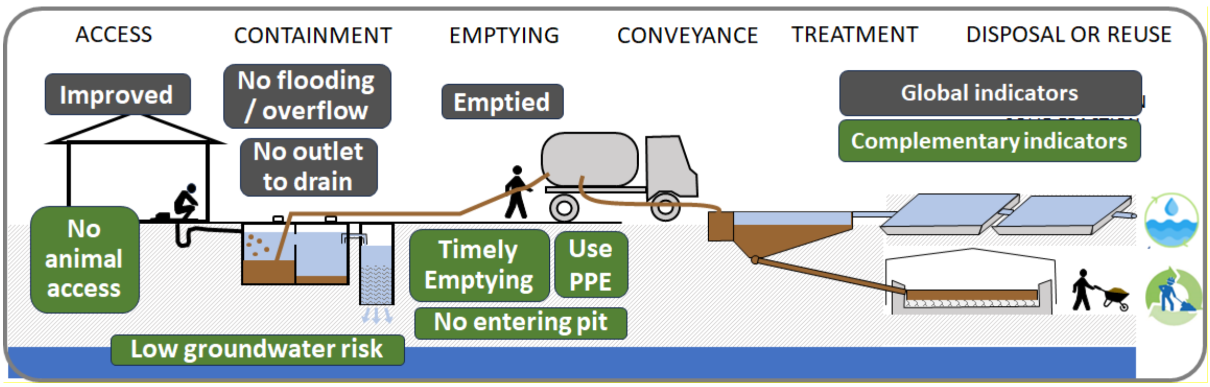

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Indicators to complement global monitoring of safely managed on-site sanitation to understand health risks

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Halfway through the Sustainable Development Goal (SDG) period, there has been little research on the criteria for monitoring safely managed sanitation under SDG target 6.2. For reporting against SDGs, global indicators are necessarily limited and exclude many safety aspects from a public health perspective. Primary survey data from 31,784 households in seven countries in Asia and Africa were analysed, comparing estimates of safely managed on-site sanitation based on global indicators with five complementary indicators of safety: animal access to excreta, groundwater contamination, overdue emptying, entering containments to empty and inadequate protection during emptying. Application of additional criteria reduced the population with safely managed sanitation by 0.4–35% for specific indicators, with the largest impact due to the risk of groundwater contamination, animal access, and containments overdue for emptying. Combining these indicators across the service chain, excluding transport and treatment, found almost three-quarters of on-site systems currently assessed as safely managed with global indicators were considered unsafe based on complementary indicators. A more comprehensive assessment of safety of on-site sanitation can be achieved through these indicators, which could be integrated into national monitoring systems and used to inform sanitation investments that address local health-related risks.

Inadequate sanitation is associated with numerous and varied health risks[1]. There are multiple sources of faecal environmental contamination from inadequate sanitation systems and multiple pathways for exposure[2,3]. The presence of a toilet is therefore an insufficient measure to indicate whether positive health outcomes are likely to be achieved by sanitation improvements[4], hence numerous authors critiqued the Millennium Development Goal target, expressed solely in terms of access to toilets[5–8]. The Sustainable Development Goal (SDG) target 6.2 of safely managed sanitation services aims to address these limitations by considering the management of excreta from the toilet to final treatment and disposal[9]. The Joint Monitoring Programme (JMP) led the development of global indicators and standardised core questions to enable consistent and practical classification of sanitation services for national and global monitoring (see Table 3)[10]. However, these indicators do not cover all aspects of safety, such as those outlined in WHO guidelines on sanitation and health[1]. The guidelines suggest countries agreeing to the SDG framework should routinely monitor and report on the global indicators, as a minimum, and suggest these are complemented by more nuanced and contextual regional and national indicators. The JMP proposed some expanded indicators, but these focus on expanded definitions of toilet access, for example, privacy of toilet use, and include limited expanded indicators related to the safe management of containments, emptying, conveyance and disposal[10]. Safely managed sanitation as defined for global monitoring, while a significant improvement in monitoring access to improved toilets, should not be assumed to indicate a service level that protects against many key faecal transmission pathways. Since what doesn't get measured doesn't get managed[11,12], relying on global indicators to prioritise investment may result in sanitation improvements that do not address critical health risks.

Despite debate and research on other aspects of SDG 6.2, there has been little assessment of the indicators for safely managed sanitation services nor exploration of the complementary indicators that could address the gaps. Numerous publications have critiqued and suggested improvements to the classification of shared toilets as limited sanitation[13], the monitoring of progress of lower service levels[14], the means of implementation targets[15,16], and explored alternatives for monitoring safely managed water services[17]. However, there has been little discussion on the formation and scope of the

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indicators for safely managed sanitation services, and even uncertainty about how services will be measured as safely managed[16]. The opinion piece by Rose et al. defined safe sanitation through a communal social lens as based on the 'social construct that lies at the intersection of knowledge, societal engagement, and controls'[18]. Rose's paper highlighted the role of the community in monitoring but did not review the indicators for safely managed sanitation or propose alternative indicators relevant to their definition[18]. Beard et al. highlighted the challenges to assessing on-site systems and the need for revised categories for improved sanitation facilities, yet they did not review indicators related to safe management across the service chain[19]. One paper proposed complementary indicators for safely managed sanitation services for national monitoring in Austria[20]. This provided valuable insights for high-income contexts with predominately sewerage services, yet was less applicable for low- and middle-income countries with predominantly on-site sanitation.

National and subnational decision-makers should not rely on global monitoring alone to inform investment. Globally defined indicators for water and sanitation may not adequately capture the national realities and challenges faced by individual countries or best suit the needs of individual countries to assess progress towards national goals[20,21]. Beard et al. argued that for urban sanitation, global monitoring efforts do not provide a clear picture of the challenge of managing excreta at the city scale and that the current indicators have a limited ability to inform policy and action[19]. This paper does not intend to critique the objective and approach of the SDGs or indicators used for global monitoring but to highlight that these indicators are an initial approach to define a 'safely managed sanitation service'. Indeed, the 2030 Agenda for Sustainable Development recommends that global indicators be complemented by indicators at the regional and national levels, which will be developed by Member States[22]. The Guidelines on Sanitation and Health also suggest more indicators are needed at the utility and sub-national levels to inform local programmes and actions[1]. Although the number of countries able to report against safely managed sanitation has increased, significant data gaps remain, particularly regarding on-site sanitation[23], making it an opportune time to inform the scope and approach to monitoring sanitation.

Beyond those currently assessed by the global indicators, there are a range of additional exposure pathways associated with inadequate sanitation systems and their management. Animal access to uncovered or inadequately protected faeces can transmit excreta and pathogens to people, surfaces and food, especially in dense settings or places where animals and humans are in close proximity[24–26]. Inadequate subsoil treatment of leachate from unsealed on-site sanitation can contaminate groundwater supplies used for drinking water, with contamination risk influenced by toilet and containment type, soil type, groundwater level and proximity to wells[27]. Poor operation and management of sanitation can also increase exposure to faecal pathogens. Infrequent emptying of on-site sanitation is associated with an increased likelihood of overflowing, malfunction or reduced performance[2]. Infrequent emptying can also lead to unsafe emptying practices, such as entering the pit to remove hardened sludge or informal emptying practices such as wash out, putting both the workers and public at risk of exposure[2,28]. The health risks sanitation workers face during emptying have been increasingly recognised, including direct exposure to faecal pathogens and risks from working in confined spaces[29,30].

While environmental sampling and detailed health exposure studies and models have improved our understanding of health risks, household surveys can assess potential exposure pathways at a larger scale and lower cost. Several tools, models and detailed research studies have developed methods to investigate critical faecal exposure pathways[25,31–33]. While they have been valuable in demonstrating the high concentration of pathogens in the environment and need to consider multiple exposure pathways, they typically require high skills or equipment and can be difficult to conduct at scale. Household questionnaires, while limited in simple questions and self-reporting, benefit from capturing sanitation data at scale for a relatively low cost when included in broader surveys. Assessment of indicators of pathogen exposure pathways cannot ensure that a system provides 100% protection against human contact with excreta; however, it can point to common failures in sanitation systems that increase the risk of exposure to prioritise improvements or further in-depth investigation. There remains an opportunity to expand household monitoring to better assess and prioritise potential exposure pathways at a larger scale than the field-based exposure assessments.

Recognising that global monitoring is necessarily limited for simplicity and comparability, this paper proposes complementary indicators that could be incorporated into household monitoring to provide a more comprehensive assessment of on-site sanitation focusing on faecal exposure pathways. While research on other aspects of SDG 6.2 led to debate and refinement of indicators (e.g., shared sanitation) for the assessment of safely managed services, as noted above, previous research identified the need for complementary indicators yet did not suggest potential indicators relevant to areas with predominately on-site sanitation, such as is common in low- and middle-income countries. SNV, an international non-government organisation, conducted baseline monitoring between 2018–2019 in 34 urban and rural districts across seven countries to inform and monitor progress of their sanitation programmes. Trained enumerators conducted surveys of 31,784 households, which included global core questions and supplementary questions related to additional exposure pathways as well as qualitative assessments of service provision. The data from health-related household questions were assessed to compare five complementary indicators with the equivalent global sub-indicators for improved, contained and emptied on-site sanitation. This research evaluated the extent to which consideration of critical exposure pathways reduced the proportion of systems classified as safely managed on-site sanitation and analysed the contexts or conditions in which different indicators may be more or less important. This research aims to address the gap in tested complementary indicators relevant to on-site sanitation that could be incorporated into sanitation monitoring systems. The research is timely as national WASH monitoring frameworks continue to be updated to improve reporting against the SDGs, and these relevant complementary indicators to enhance understanding of local health risks and inform sanitation investments.

Results

As background to the results for the complementary indicators, Fig. 1 presents the overall access to improved sanitation for the 21 urban cities (with populations varying from 21,036–2.67 million) and 13 rural districts (that may include some district centres), see Supplementary Table 1 for details of sample areas. Most households used improved on-site sanitation systems (79% average across countries), which are facilities that aim to hygienically separate excreta from human contact. A small number of households in the cities in Tanzania and Zambia used improved toilets connected to sewers (1%) and on average across countries 10% practised open defecation, predominately in rural Laos. The JMP classifies shared improved toilets as 'limited sanitation', which were used by an average of 17% of urban and 6% of rural respondents. This resulted in 65% and 71% of respondents in urban and rural areas reported accessing at least basic sanitation (Supplementary Table 2). While only 'at least basic' sanitation can be considered as 'safely managed' sanitation services, in this paper the analysis of each indicator considered all improved sanitation facilities, as both shared and private facilities contribute to faecal environmental contamination[34]. The contextual factors included the typology of improved sanitation facilities, of which 89% of households in rural areas reported the use of a pit (i.e., direct pit, off-set pit, two sequential pits, double off-set pit, composting), and 11% reported the use of a tank (septic tank, holding tank, communal septic tank) (see Supplementary Table 2). In urban areas, tanks and pits were equally reported, although this varied between countries. Containments had been in use for an average of 8.6 years in urban areas and 5.8 years in rural areas. Of improved on-site systems, 6% had previously been emptied in rural areas and 22% in urban areas.

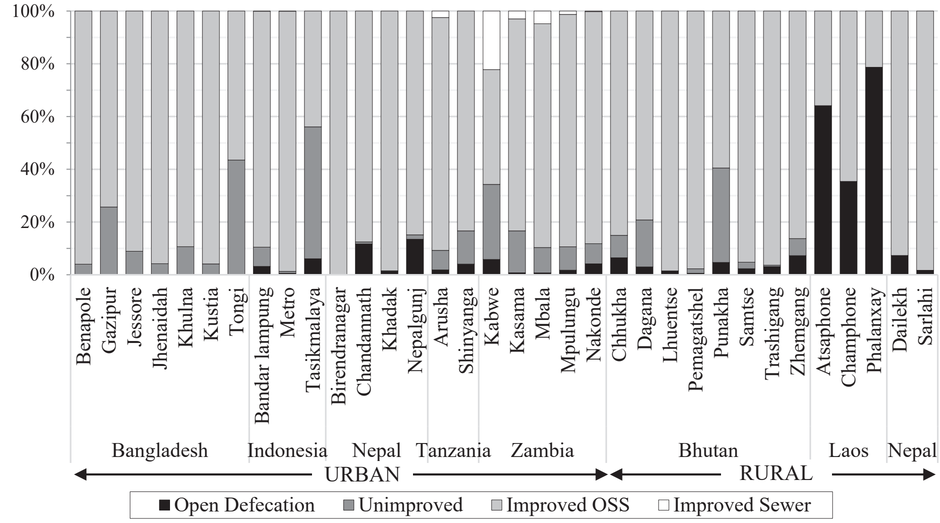


Fig. 1 | Household access to sanitation by category of facility, as defined by the JMP standard indicator set for 21 urban and 13 rural districts of seven countries based on data collected by SNV in 2018–2019. Complementary indicators were only analysed for the improved sanitation facilities.

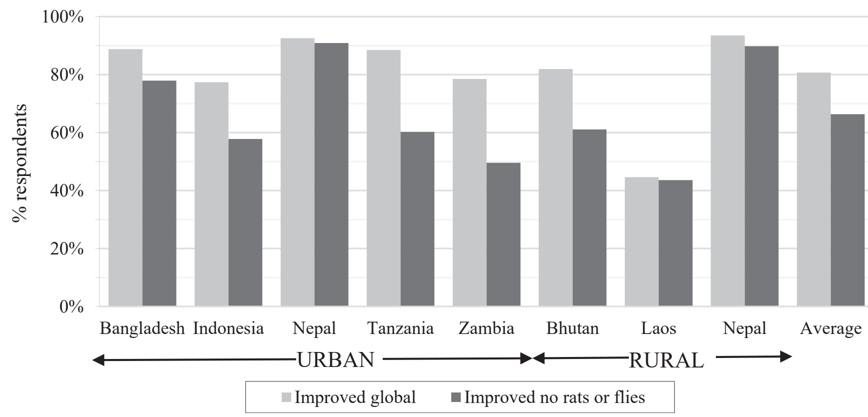


Fig. 2 | Proportion of households with access to improved sanitation considering the global indicator compared with the complementary indicator that considers toilets that are improved and not accessible to animals. Reduction in improved when considering animals was greatest for Indonesia, Tanzania, Zambia and Bhutan and lowest in Nepal and Tanzania, which also had fewer dry or composting pits.

Improved facilities: animal access to excreta

Moving beyond the high-level assessment of facility type, data was analysed to assess whether facilities classified as improved were still at risk of animal access to excreta, which can result in mechanical transmission of pathogens from animals to humans. The remaining results are presented as country averages for improved clarity in demonstrating the difference between global and complementary indicators, with the results for each of the 34 cities and districts provided in the supplementary materials. On average across all countries 81% of respondents reported using an improved sanitation facility, yet 14% of respondents used improved toilets that were accessible to rats and flies. In urban areas, the proportion of improved facilities reduced by 18% when assessed for animal access, which was a greater reduction than in rural areas (8%). The reduction varied between countries, ranging from 1% in Laos and 2% in urban Nepal to a reduction of 28% and 29% in Tanzania and Zambia, respectively (Fig. 2). The variation between cities or districts within a country was greatest for Bhutan, Bangladesh and Zambia, with the greatest impact (51% reduction) in Zhemgang district, Bhutan. Poorer households and dry toilets had a significantly greater prevalence of animal access than non-poor households or water-based toilets (Table 1).

Containment—Groundwater risk

The assessment of groundwater risk first considers the global indicator for containment, which requires that on-site systems do not discharge excreta to surface environments. The global indicator considers facilities not contained if they overflow or leak waste directly into the surface environment[10,35]. First, we present the findings of the global indicator, as the results for the complementary indicator of groundwater risk are calculated for only those systems classified as contained by the global indicator. Based on the global definition, on average across countries, 66% of respondents used 'contained' on-site sanitation and 14% used uncontained systems, made up of 8% with an outlet (i.e., overflow line) to surface environment, 4% having flooded or overflow and 1% with both outlet and overflow. In urban areas, an average 20% of respondents used uncontained systems, with the highest proportion in Bangladesh (57% uncontained), predominately due to outlets to the surface environment (45%) (see Supplementary Fig. 1 and Supplementary Table 2). In rural areas the presence of an outlet was only assessed in Nepal, 1% of improved systems had an outlet, therefore the 4% of respondents using uncontained systems in rural areas was due to issues with flooding and overflow. as SNV's rural monitoring only assessed the presence of outlets in Nepal and (1% used systems with an outlet to the environment). Factors associated with a significantly greater prevalence of facilities being uncontained were urban areas, wet containments, tanks, deep containments, and systems in deeper groundwater (Table 1). Comparing the different causes, a greater prevalence of flooding and overflow occurred for dry toilets, pits, and poorer households, while a greater prevalence of outlets to surface environment occurred for water flush containments and tanks.

While the global indicator assesses releases from on-site sanitation to surface environments, groundwater contamination from on-site sanitation is a critical exposure pathway in some contexts. A risk matrix based on literature was used to assess potential groundwater contamination risk based on household self-reported containment depth and secondary data on groundwater depth and soil type collected for each sub-district or neighbourhood. Methods are described in Table 3, with further details in

Table 1 | Prevalence ratio estimates for the strength of association between context variables and the complementary indicator

Prevalence ratio[a] [95% CI]		Context variables (household level)						
		Rural/Urban	Poorer households/ not poor	GW <5 m / >5 m	Dry/Wet containment	Pit/Tank	Age > 5 yrs/ < 5 yrs	Depth < 3 m / > 3 m
Of improved	Animal access	**0.86** [0.79–0.93]	**1.74** [1.65–1.84]	**1.22** [1.16–1.28]	**4.84** [4.63–5.05]	**2.18** [2.05–2.31]	**0.79** [0.75–0.83]	1.02 [0.95–1.09]
	Uncontained	**0.09** [0.07–0.1]	**1.15** [1.11–1.2]	**0.67** [0.64–0.69]	**0.48** [0.44–0.52]	**0.40** [0.38–0.41]	**1.81** [1.73–1.89]	**0.42** [0.39–0.44]
Of contained (Global)	Ground-water risk	**0.48** [0.46–0.5]	**0.90** [0.87–0.94]	**4.15** [4.01–4.30]	**1.08** [1.04–1.13]	**1.23** [1.19–1.27]	1.00 [0.97–1.02]	**0.50** [0.48–0.52]
Of improved	Emptied (Global)	**0.25** [0.22–0.29]	**1.24** [1.17–1.31]	**1.23** [1.17–1.29]	**0.6** [0.54–0.67]	**1.09** [1.04–1.15]	**5.41** [4.94–5.93]	1.03 [0.96–1.09]
Of improved not emptied	Overdue for emptying	**0.61** [0.57–0.66]	**0.66** [0.62–0.71]	**0.89** [0.85–0.94]	**0.47** [0.42–0.53]	**1.07** [1.02–1.12]	**98.04** [71.9–133.6]	**1.09** [1.04–1.15]
Of improved emptied	Overdue for re-emptying	**2.74** [1.44–5.2]	**0.24** [0.11–0.51]	**0.6** [0.39–0.93]	0.34 [0.08–1.38]	1.14 [0.75–1.71]	1.88 [0.77–4.6]	**3.81** [2.48–5.83]
	Entered	**1.56** [1.18–2.08]	**0.74** [0.61–0.88]	**0.62** [0.53–0.72]	**0.32** [0.19–0.55]	**0.72** [0.63–0.83]	1.03 [0.8–1.34]	1.03 [0.85–1.25]
	Inadequate PPE	**0.77** [0.7–0.86]	**1.12** [1.09–1.15]	0.97 [0.97–1.02]	1.03 [0.98–1.08]	**1.08** [1.05–1.11]	0.97 [0.93–1.01]	0.99 [0.96–1.02]

[a]Significant prevalence ratios are in bold (significance 2-sided $p > 0.05$).

supplementary materials. The analysis found an average of 35% of the population use systems classified as contained but pose a high risk of contaminating groundwater and ranged from 0% in Bhutan to 78% in Tanzania (see Fig. 3). Most countries had low and high risk areas, indicating the variability of local environmental conditions (see Supplementary Fig. 6 and groundwater depth and soil type in Supplementary Table 1). The exception was Bhutan, where no risk was found in any of the surveyed districts. Recognising that the exposure risk to potentially contaminated groundwater is most relevant when groundwater is used for drinking, further analysis, beyond SNV's current indicator, considered contamination a high risk only when 25% or more of the respondents in the district reported using groundwater for drinking. Supplementary Fig. 2 presents the adjusted results, which found the proportion of uncontained sanitation due to groundwater risk reduced to an average of 24% considering contamination risks only in areas using groundwater. This revision had the greatest impact in the two cities assessed in Tanzania, with 78% of respondents with contained on-site systems at risk to groundwater reduced to zero since groundwater is not used for drinking. Risks in urban Nepal and Zambia reduced by 4% and 5% respectively, considering some cities had low groundwater use.

Overdue emptying—unemptied stored in-situ and emptying within the timely threshold

The global indicator for emptying within the assessment of safely managed sanitation considers whether containments were ever emptied. Of all respondents, 10% had improved on-site systems that were previously emptied, 1% built a new pit, 64% were never emptied and 3% didn't know, which were considered never emptied for analysis (Supplementary Table 2). Emptying rates were lowest in Zambia, Bhutan and Laos (1 to 4%) and highest in Bangladesh (32%) (see Fig. 5). Emptying was more likely for older systems, wet containments and urban areas (Table 1).

Many types of containments require regular emptying, so they function as designed or do not overflow. Therefore, the complementary indicator assessed whether unemptied systems were overdue for emptying by comparing years of operation with a calculated timely emptying threshold. The threshold was calculated based on the number of users, containment size and sludge accumulation, estimated for each containment type and each country (see methods in Table 3 and supplementary materials). Compared with the 67% of respondents that used unemptied improved containments, considered by global monitoring as safely stored in-situ, 21% of the population had unemptied improved containments were overdue for emptying (operation years greater than the timely emptying threshold). The largest reductions due to overdue emptying occurred in Indonesia (42%), followed by urban and rural Nepal with 27% reduction, while Zambia was the least impacted by this complementary indicator (6%, see Fig. 4). Within countries, there was some variation between cities or districts, particularly in Nepal where reductions ranged from 11% to 44% between cities. Of improved on-site systems that had never been emptied, urban areas, wet toilets and non-poor households were associated with a significantly greater prevalence of being overdue for emptying, highlighting it is not just an affordability issue (Table 1). Of previously emptied systems, only an average 0.4% of improved on-site systems are overdue for re-emptying, with a maximum reduction of 0.8% of systems in Indonesia (Supplementary Fig. 8 presents disaggregated city and district results).

Emptying—Occupational health and safety risks

While 10% of respondents had improved on-site systems previously emptied, only 8% were emptied without someone entering the containment. From Fig. 5, the greatest reduction in safe emptying when considering entering was in urban Nepal (5% reduction) and Bangladesh (4%), with small decreases in Tanzania and rural Nepal (0–1%), where completely mechanical emptying was more common. Entering was more likely for containments emptied by the household or tenant (24% entered), compared with manual (15%) and mechanical (3%) service providers. Rural areas and wet containments were at greater risk of reported entering to empty,

Fig. 3 | Comparison of global indicator for containment with the complementary indicator that includes on-site systems that are contained and do not pose a high risk of groundwater contamination considering infiltration depth and soil type. The complementary indicator reduced the proportion of systems considered contained across most countries, excluding Bhutan where there is a low risk of groundwater contamination.

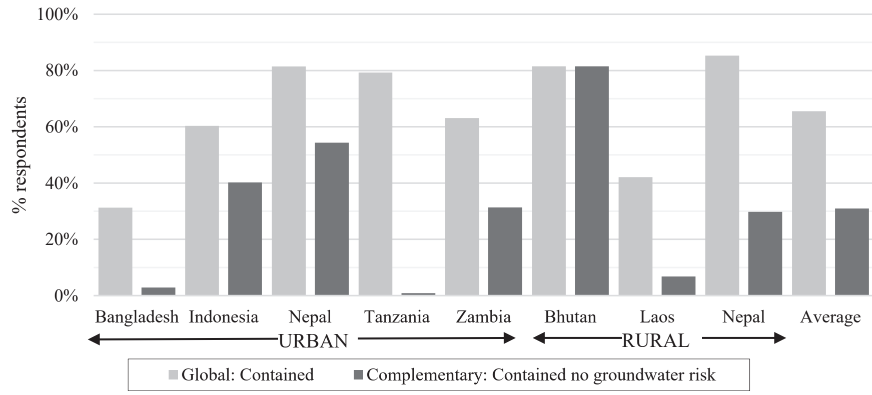


Fig. 4 | Comparison of the global indicator of households with improved on-site systems that were never emptied with the complementary indicator of improved unemptied systems not overdue for emptying. Contained and not emptied systems are considered safely managed sanitation in global monitoring. However, this complementary indicator demonstrates many of these systems have operated beyond the emptying threshold and are likely full of sludge and at risk of reduced function or overflow.

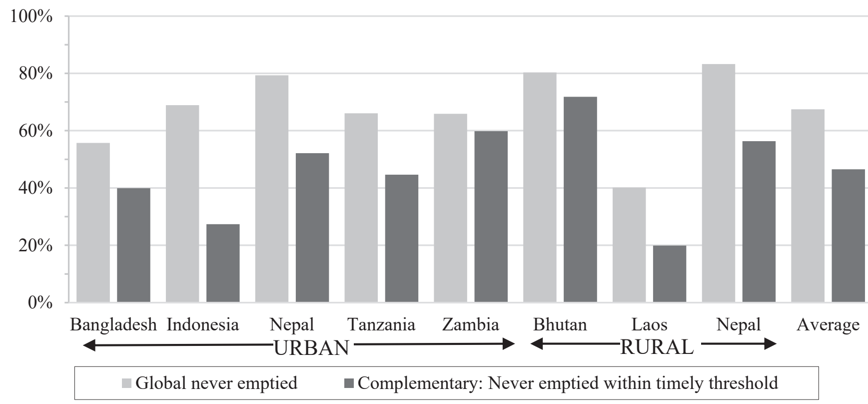
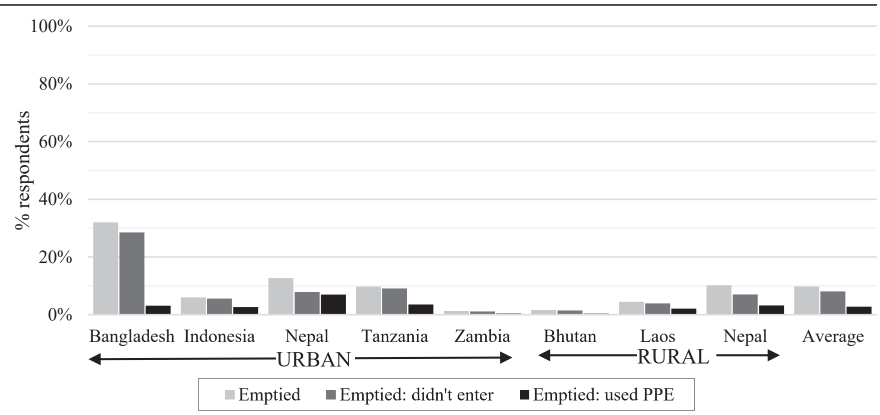


Fig. 5 | Comparison of ever emptied systems with those emptied following health and safety practices. Much higher rates of emptying occurred in Bangladesh with the complementary indicator of use of PPE having much greater impact than entering in all countries.



although rural areas were also more likely emptied by users (35%) than urban areas (6%) (Table 1).

The other health and safety indicator was the use of a minimum level of personal protective equipment (PPE), including boots, gloves and a mask. Across all countries, only 3% of respondents used improved on-site sanitation emptied with adequate PPE. The lowest compliance was in Bangladesh where 32% of improved on-site systems had been emptied, yet 29% were systems emptied without minimum PPE. The next largest reduction was in Nepal and Tanzania where 6% of respondents used improved containments emptied without minimum PPE (Fig. 5). Greater PPE compliance was reported for containments emptied by the household than those emptied by service providers and for manual rather than mixed or fully mechanised emptying, noting this data was self-reported. There was slight variation between cities for both indicators, except for Bangladesh only 1–4% of respondents reported systems emptied with adequate PPE despite emptying ranging from 11–44%. The prevalence of inadequate PPE was significantly greater for urban areas and poorer households (Table 1).

Influence of context variables on the significance of complementary indicators

Analysis of the associations between contextual factors and complementary indicators can inform which indicators or exposure pathways may be most important in specific contexts, recognising that not all indicators may be necessary everywhere. Table 1 indicates which technological, socio-economic and environmental factors were associated with an increased probability of systems failing each indicator. Note that this approach examined factors independently and did not account for the influence of other variables. Compared with rural areas, on-site sanitation systems in urban areas were more likely to be at risk of contaminating groundwater, be overdue for emptying and pose a hazard to workers without adequate PPE.

Table 2 | Proportion of respondents meeting global and complementary indicators (I) and the average reduction in the proportion of the population assessed a safe due to each individual complementary indicators average across all countries and per country (II)

Global and complementary indicators	(I) Total respondents assessed as safe for each indicator[a]	(II) Reduction in the population considered safe due to complementary exposure pathways (Reduction% = Global% – Complementary%)									
		All countries		Urban					Rural		
		Ave	Std Dev	BGD	IDN	NPL	TZA	ZMB	BTN	LAO	NPL
Improved (Global)	**81%**										
Improved and no animal access	66%	14%	12%	11%	20%	2%	28%	29%	21%	1%	4%
Contained (Global)	**66%**										
Contained and low groundwater risk	31%	35%	24%	28%	20%	27%	78%	32%	0%	35%	56%
Not emptied (Global)	**67%**										
Not emptied and not overdue for emptying	46%	21%	11%	16%	42%	27%	21%	6%	8%	20%	27%
Emptied (Global)	**10%**										
Emptied, not overdue for re-emptying	9%	0.4%	0.3%	0%	1%	1%	0%	0%	0%	1%	0%
Emptied, didn't enter pit	8%	2%	2%	4%	0%	5%	1%	0%	0%	1%	3%
Emptied, adequate PPE	3%	7%	9%	29%	3%	6%	6%	1%	1%	2%	7%

[a]Global indicator response rate in bold. Reduction is the difference between the response rate for global indicators minus the repsonse rate for complementary indiactors.

However, the likelihood of workers entering an on-site sanitation system for emptying purposes was greater in rural areas. Compared with median and upper income households, lower-income households were less likely to have systems that were overdue for emptying or be entered by workers for emptying. On-site sanitation systems in areas with shallow groundwater (<5 m) were more likely to pose a contamination risk to groundwater and be accessible to animals, but were less likely to be overdue for emptying or require workers to enter them to empty. Compared with flush or wet containments and tanks, dry containments and pits were more likely to be accessible to animals and pose a risk to groundwater, yet less likely to be uncontained or be entered to empty. Compared with recently built containments, older containments (>5 years old) were more likely to be uncontained and overdue for emptying but less likely to be accessible to animals, with no significant difference in entering to empty.

Overall analysis of the difference between global and complementary indicators

Table 2 shows the proportion of households meeting global indicators considering the existing definition used by the JMP for global monitoring of safely managed sanitation (on the left). The columns to the right show the reduction in this proportion when considering additional potential exposure pathways of the complementary indicators, including the overall and country average reduction for each indicator. The complementary indicators resulting in the greatest reduction in the proportion of respondents considered safely managed were the indicator of groundwater risk (35% reduction), followed by unemptied containments overdue for emptying (21%) and animal access (14%). While 10% of households had emptied their on-site system (global indicator), very few of these are overdue for re-emptying, and this indicator had the lowest impact (0.4% reduction). Indicators had varied impacts between countries; for example, in Bhutan, animal access caused the greatest reduction, which may be associated with the high use of dry pits, whereas in Laos, considering animal access had a minor impact, while groundwater risk and overdue for emptying had the largest impact on safety. Within-country variability was lower than between-country variability for most indicators except groundwater risk, which had equally high variability within-countries as between-countries (Supplementary Table 8).

While the indicators were analysed and presented separately to highlight their individual impact and variation between contexts, safely managed sanitation requires cumulative analysis across the service chain as excreta must be managed from containment to treatment. The data allowed for cumulative assessment of safely managed sanitation services considering each household's response across the service chain (improved, contained, emptied and stored in-situ), recognising that households may fail multiple steps and only achieve safe management if all steps were assessed as safe. A full assessment of safely managed services for systems emptied and disposed off-site was not possible since transport and treatment data was not, and cannot be, collected through household surveys. Therefore the assessment of safely managed sanitation included (a) on-site systems that were contained, not emptied and safely stored in-situ, or (b) emptied and buried in-situ, or (c) potentially safely managed if contained, emptied and removed offsite but with unknown disposal and treatment. Figure 6 shows the results of the combined analysis across the service chain, comparing global indicators with complementary indicators and showing those safely managed by storage in situ (assessment possible with household surveys) and those that are potentially safely managed, assessed up to emptying but not transport and treatment. Considering global indicators, overall 56% of respondents accessed safely managed on-site sanitation services up to emptying, although a proportion of the 5% emptied could be unsafe if not adequately transported and treated. The proportion of households meeting global and complementary indicators was 16%, just over one-quarter of the value found using global indicators only. The difference was larger in urban areas, where the assessment with complementary indicators reduced the proportion of households with safely managed services to just over one fifth of the estimate with global indicators, while in rural areas it was one third. The largest differences were in Bangladesh and Tanzania, where the proportion of households with safely managed services based on global indicators was 26% and 52% respectively compared with 2% and 1% safely managed considering complementary indicators (Supplementary Fig. 3). Laos and rural Nepal had the next largest reductions with the proportion safely managed considering complementary indicators around one tenth of the result using global indicators. Bhutan was the least impacted with complementary indicators resulting in an estimate two-thirds the estimate of safely managed sanitation with global indicators.

Discussion

While the SDG global indicator 6.2.1a 'use of safely managed sanitation services' is an improvement on the monitoring of basic access to toilets, the findings from the analysis of complementary indicators suggest that several faecal exposure risks may remain. There was a stark reduction in the

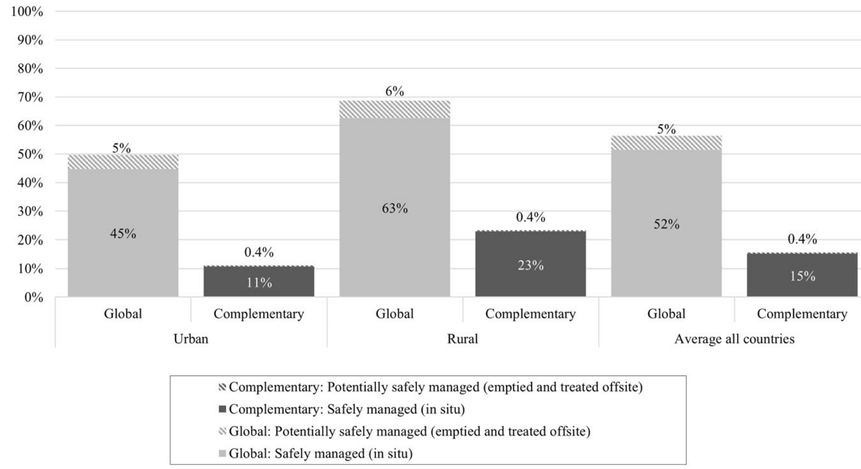


Fig. 6 | Comparison cumulative estimate safely managed on-site sanitation (excluding transport and treatment) for the global and complementary indicators. Cumulative estimates shown for urban, rural and all respondents and disaggregated by those safely stored in-situ and those safely emptied.

combined estimate of safely managed on-site sanitation from 56% using global indicators to 16% considering five complementary indicators. In all countries, more than one third of systems assessed as safely managed sanitation were considered unsafe based on complementary indicators. Considering the five individual indicators, as these are what can inform where and what to improve across the service chain, the reduction for each complementary indicator compared to the global indicator ranged from 0.4% to 35%. Including these indicators in sanitation monitoring can significantly change whether a sanitation system should be perceived as truly safe, even if it does meet the global criteria for 'safely managed'. The indicator on groundwater risk had the largest impact, with 35% of systems classified as contained with the global indicator assessed as a high risk for contaminating groundwater. Overdue emptying and animal access had the next greatest impacts, reducing the proportion assessed as safely managed by 22% and 14%, respectively. Given that only 10% of improved systems had ever been emptied, it was not surprising that the complementary indicators on emptying had the lowest overall impact but when considered as a proportion of the emptied systems, these risks remain important. A substantial number of on-site systems failed each indicator to warrant further consideration or uptake of all assessed indicators given the ongoing risks to public health if these exposure pathways are not addressed.

Assessing the individual indicators rather than the overall combined estimate was also important given the variability of risks between and within-countries. In many countries sanitation decisions and investment occur at a sub-national scale, therefore data should be disaggregated to the level needed to inform these decisions[19,36]. Data and risk assessments at a local scale were also emphasised by citywide inclusive sanitation (CWIS) planning and WHO's sanitation safety planning[37,38]. The impact of the complementary indicators varied both between and within countries which indicated that many risks were context-specific and that global or national assumptions about the priority aspects of safely managed sanitation were unlikely to apply to all sub-national contexts (see disaggregated findings in supplementary materials). Indicators with the greatest between-country variation were groundwater risk, which was high in Tanzania (78% reduction) and zero in Bhutan, and the use of adequate PPE during emptying, which was most impactful in Bangladesh but low in other countries where emptying rates were also low. Within country variation was most evident for groundwater risk, highlighting that decisions on groundwater risk from on-site sanitation are unlikely to be globally or nationally applicable but may be very important in some contexts.

Resources for monitoring sanitation are often limited, therefore this research can inform which contexts specific indicators may be more critical. There remain concerns that monitoring is expensive and diverts funds from already sparse resources for implementation, and debates whether indicators are selected and used to inform decisions[16,21]. Others argue that the limited resources further emphasise the need for careful indicator selection and sufficient data to support decision-making[20,21]. The analysis of prevalence ratios found some contextual factors had prevalence ratios as expected, such as older on-site systems facing a greater prevalence of being overdue for emptying. In contrast, other ratios were less predictable, such as tanks and wet containments associated with a higher prevalence of being entered to empty (rather than externally with a pump) or that poorer households were associated with a lower prevalence of overdue for emptying. Overall, each indicator was found to be important in certain contexts and therefore should be considered for inclusion in local and national monitoring. However, not all indicators will be relevant in every context and the selection of variables should consider whether the context variables or other factors suggest the indicator may be less relevant. For example, if the groundwater is known to be deep in all of Bhutan, the groundwater risk indicator would be unnecessary to monitor or just included in the districts with potentially shallow groundwater. While it may be challenging to decide what indicators will be critical before data collection, this analysis, along with existing background information could be used, or indicator selection could be informed by small pilots or guided by national priorities.

The indicators and methods presented in this paper are not perfect, yet they show a tested way forward to improve monitoring of on-site sanitation that can potentially be integrated into household surveys or routine monitoring systems. Previous research has highlighted the role of development partners in supporting monitoring improvements and national partners through capacity development and data collection, yet noted there was still a lack of tested methods, indicators and recommendations that were directly usable by national governments[16]. National monitoring systems are slow to adopt new indicators and require evidence of testing at scale and their impact on sanitation systems to be receptive to new approaches[39]. Further research could improve complementary indicators, such as refining the indicators on groundwater risk or timely emptying with locally relevant data rather than global assumptions, and further evidence on the relationship between infrequent emptying and groundwater contamination on faecal exposure in different contexts. Other indicators could be included to further understand the cause of the risks, such as why systems are overflowing or being entered to empty, however, there are limits to what can be asked to households as other sources of data may be needed for more technical assessments of containment design and function, or assessment of the availability of mechanical emptying equipment. Research has shown that provision of PPE alone is insufficient to protect public health and also that it is difficult to assess use[30]. Therefore, other indicators for sanitation workers' health and safety may be selected based on local issues or service objectives, with some examples provided in SNV's outcome indicators[40]. Lastly, while we discuss health risks, it is also important to recognise that these indicators assess the hazards and there remains limited research on the exposure and illness associated with sanitation related hazards; therefore direct health benefits cannot be guaranteed from achieving these indicators[41].

Nevertheless, investments that address these hazards will progressively reduce pathogens in the environment and contribute towards improved public and environmental health.

The study does not intend to be an exhaustive analysis of all possible indicators for sanitation for different objectives and data sources and instead focuses on a set of recommended household survey questions relevant to identifying and reducing health risks. A limitation of this scope was the exclusion of health risks associated with the transport, treatment, and final disposal, which cannot accurately be assessed from household surveys[42]. The global indicators for transport and treatment are the 'proportion delivered' and whether 'excreta from on-site sanitation receives solid and liquid treatment'. Complementary indicators could also be developed for these steps, for example, public health risks associated with excreta spilled during transport or the actual operation and performance at treatment facilities and the health risks of treatment effluent. Complementary indicators could also be developed to inform other drivers for sanitation investment, such as indicators relevant to environment, finance, equity, service viability, household preferences, etc. Although the sampling presented a diversity of contexts, it was not nationally or globally representative, and testing these indicators in other contexts could confirm their applicability to different settings. Further testing and research on public health risks associated with on-site sanitation could further refine data collection methods and assumptions, particularly locally relevant assumptions for timely emptying and the groundwater risk matrix or to test the sensitivity of the results to different assumptions. Further research could also investigate how other methods of data collection, such as remote sensors, spatial mapping or citizen science, could contribute to, or reduce costs, of montioring sanitation and related health risks[43–45].

Despite being halfway through the SDG period, there has been little discussion about how this service level of safely managed sanitation is defined and monitored. This paper found that, in many cases, on-site sanitation systems continue to pose a substantial health risk, even if classified as 'safely managed' using global indicators and definitions. This is largely because the currently available national data used for global monitoring does not assess all significant exposure pathways. While SDG monitoring created a valuable shift in attention beyond the toilet, national and local monitoring systems need to go beyond the SDG global indicators and integrate additional indicators to enable a more comprehensive assessment of health risks associated with sanitation services. Recognising that household surveys will continue to be a main source of data for on-site sanitation in many low- and middle-income countries, this research suggests that the five indicators analysed can improve the assessment of whether a toilet, on-site sanitation system or emptying practice, poses a hazard to public health. We recommend national and local monitoring systems include these pre-tested indicators to enable a more comprehensive assessment of health risks associated with on-site sanitation. However, indicators should be selected relevant to the context, as not all indicators are relevant everywhere. This paper aims to ignite further debate on the extent to which 'safely managed sanitation' is actually safe from a health perspective and that the global definition of safely managed sanitation should not be the uppermost service objective if the ultimate goal is to end human exposure to faecal waste. We recommend further research into whether these or other complementary indicators for safely managed sanitation are critical to assess faecal exposure pathways prevalent in other contexts and to ~~inform~~ further refin~~ements of~~ the proposed data collection and analysis methods. As many countries continue to update monitoring methods to address SDG data gaps, the indicators tested in this paper can be applied immediately in monitoring frameworks and the results can be used to develop even stronger global monitoring systems and inform the post-2030 objectives.

Methods

Data collection through household surveys was designed and implemented by SNV, a not-for-profit international development organisation that works on water, energy and agriculture in 26 countries in Asia and Africa. This paper draws upon the work of their WASH programmes, where they support local governments to improve sanitation services through urban and rural sanitation and hygiene programmes. These indicators were included in their standardised performance monitoring framework[46], initially developed in 2010, which also includes other aspects not analysed in this paper, such as off-site sanitation, hygiene and solid waste, and outcomes indicators on service delivery capacities and performance. SNV performance monitoring framework uses ladders for each step of the service chain that combines multiple sub-indicators of functionality, sustainability and risk. This paper presents the sub-indicators separately for clarity and ease of applying the indicators to other monitoring frameworks.

Data collection

In partnership with local governments, SNV conducted baseline monitoring between 2018 and 2019 in 18 urban and 13 rural districts across seven countries in Asia and Africa. A total of 31,784 households were surveyed, with 26,436 households in urban cities and 5348 in rural districts (that include some district centres). In three Bangladesh cities (Jhenaidah, Khulna and Kushtia), the baseline survey included slightly different indicators; therefore the mid-term data collected in 2019 was used in this analysis for consistency. SNV received approval from each of the individual countries to collect the data and obtained informed consent from all respondents and data was anonymised by SNV for every survey. The University of Technology of Sydney Human Research Ethics Committees conducted an ethical review of the data use and analysis which was approved on 6 July 2021 (UTS HREC ETH20-5620). The standardised survey tools were translated into local languages and implemented with mobile phone-based technology (AKVO Flow). Enumerators were either local government staff or hired enumerators, managed and trained by SNV staff. A multi-stage sampling method was adopted, with the primary sampling unit of wards and districts from the programme locations previously determined by the national government. The proportion method for sample size was used to determine district/ward sample size, assuming a 5% level of significance and 2–3% margin of error. The secondary sampling unit (SSU) was country-specific; for example, in Indonesia it was village (*Kelurahan*), which were randomly selected, and samples were distributed proportionally to the village population. In areas where there were administrative units below the SSU (i.e., neighbourhoods), further random sampling was done and each selected neighbourhood was allocated an equal number of households to be surveyed. Systematic sampling was used to identify the household within each neighbourhood or village. Sample size and details of each city or district are provided in Supplementary Table 1.

Complementary indicator data collection and analysis

The indicators and data collection approaches were developed for SNV's global sanitation and hygiene monitoring framework for their multi-year urban and rural sanitation and hygiene programmes. The indicators were selected to go beyond the global indicators (see Table 3), recognising that monitoring smaller incremental changes allowed for greater learning and pathways for sanitation service improvements. SNV assessed 40 complementary impact indicators, including a range of behavioural elements (e.g., functionality, use, maintenance), hygiene, and health and safety, as well as outcome indicators to assess service provision qualitatively. The indicators analysed in this paper were a selection of the most relevant impact indicators to assess health risks along the sanitation service chain from toilet to emptying. The global indicators presented in Table 3 are based on the current approach to monitoring SDG 6.2.1a as explained in the recent progress reports, although it is recognised that many countries do not yet collect data on all of these indicators, particularly containment and emptying. Table 4 presents the data collection methods, predominately household questionnaires but also enumerator observation and secondary data for the groundwater risk assessment. Further details of the analysis of groundwater risk and timely emptying are presented in the supplementary material.

Table 3 | Comparison of global and complementary indicators and literature justification for indicators selected

JMP global indicators[10]	Complementary indicators	Justification
Improved toilet facilities[a] include flush/pour flush toilets connected to piped sewer systems, septic tanks or pit latrines; pit latrines with slabs; and composting toilets.	Animal access to excreta: Rats and flies cannot enter and exit the toilet or containment	The JMP indicator of an improved toilet is defined as hygienically separating human excreta from human contact. Although some currently included criteria applied to the assessment of improved sanitation are relevant to animal access, such as slabs on pit latrines and excluding unenclosed faeces such as hanging latrines, these criteria do not directly address fly or vermin access to excreta. The following evidence highlights the importance of the exposure pathway of animal access to excreta. - Insects can transport pathogens from excreta to people, surfaces and food[24,26,47,48]. - Flies have been shown to carry a variety of enteric pathogens, including bacteria and protozoa[49–51] - Flies can transmit high levels of faecal contamination to exposed food, especially in high-contamination settings such as slums or markets[24] but also in rural areas[26]. - Flies are abundant in urban areas when unsanitary conditions prevail and frequently contact excrement, especially when they are poorly contained[47]. - Rodents and insects are known vectors of human pathogens and diseases, are are attracted to on-site saniation systems yet literature directly linking human pathogens and outbreaks of diseases transmitted by vectors from pit latrines to humans is still scarce[52,53].
Contained: On-site sanitation facilities that do not overflow or discharge excreta directly to the surface environment[b].	Groundwater risk: Low risk to groundwater from subsurface leaching of pits or tanks	Globally, half of the world's population relies on groundwater for water supply, and half also use on-site systems for sanitation[35]. This combination poses a risk of faecal pathogens contaminating the drinking water of many hundreds of millions of people worldwide[54]. Subsurface infiltration of liquids is a crucial component of most on-site sanitation systems and is the mechanism relied on to treat faecal pathogens. However, in certain conditions due to soil type, groundwater level or hydraulic loading, sanitation systems can contaminate groundwater supplies[1,55]. Recent reports indicate that a high proportion (typically 30-50%) of water from wells contains faecal indicator bacteria, such as E. coli or faecal coliforms[54]. Studies in both high- and low-income countries have shown a link between well contamination and on-site sanitation[56]. Although the mechanism of contamination cannot always solely be attributed to sanitation due to numerous potential local or other contamination pathways[27,57]. Pathogen transport in soil and groundwater varies significantly, with viruses and bacteria found to travel 2-50 m depending on the pathogen and ground conditions[27]. While these variations have made it difficult to set standard limits on siting or use of on-site sanitation in areas of groundwater use[58], the most commonly reported factors that influence contamination risk are soil type and groundwater depth. A greater risk of contamination is expected for permeable soils such as coarse sand, gravel, and fractured rocks[27]. Groundwater depth is important as saturated soils can reduce pathogen removal and increase transport. Groundwater levels near or above the pit base have been shown to increase the pathogen horizontal travel distances compared to unsaturated conditions[58] and an adequate infiltration depth (i.e., >2 m) is needed to reduce microbial contaminants to minimal levels[59].
Disposed in-situ: Improved on-site sanitation facilities that are contained, not emptied and stored on-site. (Also relates to Emptying – see below)	Not emptied OSS within timely threshold: Pits or tanks not emptied and not overdue for emptying Emptied OSS within timely threshold: Pits or tanks have been emptied and not overdue for re-emptying	The global indicator for emptying assesses whether containments have ever been emptied. If contained and emptied, containments can be considered safely managed if excreta are buried in a covered pit on-site or if there is evidence that faecal sludge is delivered to a treatment site and treated. Never emptied containments, if assessed in the previous step as contained, are considered to be safely managed by treatment and disposal in-situ, irrelevant of how long they have been operating. The global indicator focuses on the transport of removed faecal sludge given the evidence that a high proportion is not delivered to treatment[60]. However, it does not consider the varied occupational and environmental health and safety issues associated with infrequent emptying. These include reduced performance of septic tanks operating longer than designed[61] and high solids in effluent causing clogging of infiltration systems; allowing containments to overflow to surface before emptying[62]; full pit latrines being washed out into drains or floodwaters[19,62]; settled sludge hardening and

Table 3 (continued) | Comparison of global and complementary indicators and literature justification for indicators selected

JMP global indicators[10]	Complementary indicators	Justification
		difficult to remove by mechanical pumps; or emergency emptying when toilets or pits overflow often leading to unsafe emptying practices[63]. Low emptying rates may also indicate where there are inadequate emptying services or low awareness of the need for emptying.
Emptied: Improved on-site sanitation storage facilities with containments (septic tanks or latrines) which have ever been emptied.	Emptying health and safety risks: Emptying of containments does not pose a health and safety risk to workers or the public	Emptying on-site sanitation is an activity that presents many health risks to the sanitation workers involved in emptying, as well as the owners of the containment and surrounding community. A systematic review of the health risks among sanitation workers found evidence of sanitation workers being at an increased risk of gastroenteritis and respiratory conditions and may be at increased risk of musculoskeletal disorders and mental/social health conditions[64]. Studies in India and Africa identified multiple possible safety hazards and workers exposed to various occupational risks, including exposure to faecal pathogens, heavy labour, working in confined spaces, and the use of hazardous chemicals, which could lead to injuries, illnesses, and death[29,30]. While both manual and mechanical emptying are accepted practices in the indicators for SDG 6.2.1 and in the WHO Guidelines for Sanitation and Health, risks were found to be more acute for manual or informal emptiers, with some countries prohibiting manual emptying[1,65]. The guidelines recommend minimising manual emptying where possible and avoid entering pits by transitioning to pumps[1]. Correct and consistent use of PPE was a commonly suggested approach to reduce occupational risks, however, it has been recognised that the use of PPE is a challenge and poor fitting or unsuitable equipment and lack of availability, particularly for informal workers, remains a challenge[29,30]. Many papers emphasised that PPE alone is inadequate to reduce health risks from emptying and regulation, enforcement, finance and behaviour change are needed, as well as more data about sanitation workers needs and challenges[1,29,30].

Table 4 | Methods for data collection and analysis for complementary indicators

Indicators	Question[a]	Method and analysis
Animal access to excreta: Rats and flies cannot enter and exit the toilet or containment	Can rats access the faeces in any way? If not, does the toilet pan or slab allow flies to enter and exit the pit?	Where possible this was observed and if not it was asked to the respondent. Rat access was assessed by observation of the type of pit structure, with hanging latrines and pits without a slab allowing rat access, as well as pits without covers or water seals not funcioning. For fly access, observation of the toilet water seal, pan cover and covering or mesh on vents.
Contained: On-site sanitation facilities that do not overflow or discharge excreta directly to the surface environment.	Is there an effluent outlet? Where does the effluent go? Does the toilet flood at any time of the year? Does the pit or toilet leak, overflow or flood at any time of the year? If so, how often does it leak or overflow?	The global indicator for contained was assessed by two sub-indicators Firstly, the outlet, sometimes referred to as overflow line, was assessed through 'Is there an effluent outlet?' and 'Where does the effluent go?'. Systems were classified as uncontained if there was an effluent outlet discharging to surface environments (i.e., streets, open fields, drains, streams and other waterways).[b] Secondly overflow or flooding were assessed as whether the toilet flooded at any time and whether there was leaking, overflow or flooding more than once in the last year.[c] If either or both of these were positive, the system was assessed as uncontained.
Groundwater risk: Low risk to groundwater from subsurface leaching of pits or tanks	Household questionnaire: How deep is the toilet pit below the surface? What is the main water source for drinking in this household? Non-household survey data: What is the predominant soil type? What is the typical depth of groundwater?	As this indicator is considered to go beyond the global indicators, the analysis was only for systems classified as contained based on global indicators. Soil type and groundwater depth for each neighbourhood or sub-district were sourced from secondary data (government maps and databases) and interviews with government environmental staff, well drillers and local leaders. Groundwater risk was assessed based on a risk matrix considering soil type and infiltration depth from the British Geological Society Guidelines for Assessing the Risk to Groundwater from On-Site Sanitation (AGROSS Table 4.3)[66]. This indicates that an infiltration depth less than 5 m is always unsafe, greater than 20 m is always safe, and between 5–20 m is unsafe in coarse sand, gravel and fractured rock, but safe in other soil types. The infiltration depth was calculated as the difference between the groundwater depth from the secondary data (using the upper limit of the range, see Supplementary Table 1) and containment depth from household

Table 4 (continued) | Methods for data collection and analysis for complementary indicators

Indicators	Question[a]	Method and analysis
		self-reported depth, limited to a maximum of 10 m as deeper estimates were considered unrealistic (see Supplementary Table 5). 3% of households did not know the depth of their containment, and therefore, this population was excluded from the calculation. If the result of the matrix was high risk, the system was considered not safely contained. The analysis also assessed the proportion of cities or districts using groundwater sources (all types of wells, bores and springs) for drinking water supply, although this was not included in the complementary indicator.
Timely emptying: Unemptied pits or tanks, age below timely emptying threshold. Timely re-emptying: Years since pits or tanks were emptied within timely emptying threshold	Where do the faeces go after the toilet (i.e., pit, tank, drain)? How old is your toilet (pit/tank)? Has the pit or tank ever been emptied? When was the last time the pit or tank was emptied? (if emptied)	The timely emptying threshold was the calculated number of years of operation after which the containment was expected to be full of sludge and require emptying (or alternatively, the construction of a new pit for pit latrines). Given containments are different sizes and fill up at different rates which vary with context, national estimates of timely emptying thresholds were calculated for different containment categories (single and double pit latrines, single and double composting latrines and septic tanks). The threshold was calculated from existing national data or rapid assessments of the average containment volume, number of users and sludge (blanket) accumulation rates based on literature. For pit latrines estimates of sludge accumulation range from 19–70 L/c/a, with 40 L/c/a suggested for design which was the assumed value for dry or composting toilets[67–69]. For septic tanks and wet pits, data ranged from 13–54 L/c/a and recommended values for design for wet pits of 60 L/c/a and 80 L/c/a for septic tanks based on literature from South Africa and unpublished data from Malaysia wastewater authority sludge emptying programme were adopted for the analysis[67,70–72]. More sludge accumulation data relevant to different containment types and contexts would improve the estimates and national sludge accumulation data would be preferred. For containments that have never been emptied, to be considered safely treated and stored in situ the age of the toilet must be less than the timely emptying threshold, allocated based on country and containment type. For emptied systems, as self-reported by households, the time since previous emptying must be less than the threshold to be considered safely emptied. Unknown emptying responses were classified as never emptied as per global monitoring. Given emptying relies on self-reporting, other methods could be employed to improve the accuracy of this response, but may depend on the context (e.g., receipts of emptying service, regulator or service provider data on emptying rates). Pits that were covered when full and a new one built were considered safe, as per the global indicators. The time emptying thresholds for urban and rural areas are provided in supplementary materials Supplementary Tables 6 and 7.
Emptying health and safety risks: Emptying of containments does not pose a health and safety risk to workers or the public	To empty the pit, did someone need to enter the pit? Did you observe any of the following safety measures during emptying? (use of boots, gloves and a mask)	For containments reported as previously emptied, the first question assessed whether someone entered the pit or tank to empty. This was asked separately from the PPE question due to the high risk of this behaviour. The second question was a multiple-response question, asking whether the respondent observed any of the health and safety practices related to protective equipment, of which all three were required to be considered safe, while a response of some or none was considered unsafe.

[a]The household questions and response categories are provided in supplementary material Supplementary Table 9.
[b]While outlets should be considered for all containments, in SNV's monitoring framework it was not included in rural areas of Bhutan or Laos as pre-testing indicated this practice did not occur in rural areas.
[c]Note these questions differ slightly from the questions in the JMP Core questions[10] and the recently included question in UNICEF's household surveys (MICS7) that assesses releases of excreta to the surface through overflow, floods or containment collapse[73].

Data analysis

The objective of the data analysis was to quantify the extent to which the complementary indicators changed the assessment of safely managed sanitation, compared with the current global indicators, as defined by the JMP. The data were first analysed to determine the respondents with at least improved sanitation (as defined in Table 3 and presented in Fig. 1). The complementary indicator analysis was only conducted for households with improved sanitation facilities. While safely managed sanitation is only assessed for basic facilities (improved facilities that are not shared), this would have substantially reduced the complementary indicator analysis from Tanzania and Zambia, where sharing was high, and the health risks assessed are equally relevant to both shared and not shared facilities. The indicators were presented for each step and then combined along the chain until the emptying step, as the safety of transport and treatment cannot be determined from household monitoring, which was the scope of this research. Cumulative assessment was possible for each respondent due to the availability of a single dataset that included multiple indicators, which is often not the case for global monitoring data which typically relies on ratios for cumulative assessment. Good quality data management and analysis is necessary to enable this type of analysis which can also permit disaggregated analysis considering inequalities and gender.

The prevalence ratio of the association between contextual variables and the complementary indicators being safe or unsafe was analysed using SPSS v28.0. The variables (or risk factors) included rural vs. urban, poorer households (lowest two wealth quintiles based on country specific assessment of assets) vs. not poor, groundwater depth less vs. more than 5 m, dry containments vs. wet (pour or cistern flush), pits (all types) vs. tanks (septic, holding tank), toilet age more vs. less than 5 years old, containment depth less vs. greater than 5 m. Associations of prevalence were considered significant if the 2-sided *p*-value was less than 0.05. This analysis does not propose a correlation between indicators and variables since other factors may influence but aims to inform which contexts the indicators may be more critical to monitor.

The results were presented per country and with the overall country average rather than total responses, given that sample sizes varied between countries. Data disaggregated at the city or district level are presented in supplementary materials. References to country findings were representative of the cities or districts assessed (see Supplementary Table 1) and were not nationally representative.

Data availability

The data that support the findings of this study are available on reasonable request from the corresponding author. The data are not publicly available due to them containing information that could compromise research participant privacy.

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Author contributions

F.M., J.W., R.M. and A.K. contributed to the initial conceptualisation of the work. G.H., R.M., A.N. and A.K. designed and managed SNV's data collection and A.N. collated and cleaned the datasets. F.M. analysed the data for this paper with support from T.F., J.W. and B.E.; F.M. composed the manuscript drafts and all authors provided comments and revisions to the drafts. All authors approve of the submitted manuscript.

Competing interests

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PART IV
DISCUSSION AND CONCLUSION

7. Discussion

Synthesis of findings in response to research questions

7.1 Introduction

This section summarises the findings from the four research articles, reflecting on how they address the research questions and advance understanding of how on-site sanitation is implemented and monitored to reduce public health risks. The chapter begins with a summary of the four articles: a scoping literature review that examined cost, climate and contamination drivers for sanitation decision-making and three empirical studies that assessed OSS-related health risks considering diverse risks and applying different methods.

The subsequent discussion integrates the findings across the different studies in response to the research questions, as well as contextualising them within existing literature, and considering how they may influence sanitation decisions to reduce risks. Key themes include the non-compliance of OSSs with design standards or guidelines, as well as the diverse OSS failures that compromise their effectiveness to prevent the release of excreta into the environment and to reduce human exposure. The discussion also explores how discourse and standards shape risk considerations in sanitation implementation. Context-specific data is critical given implementation and risks vary, particularly with the type of sanitation, environmental factors and the environment they are installed. The findings question the universal applicability of generic categories and assumptions. Global and local monitoring provide complementary insights on risk prevalence and severity across different scales, enabling data tailored to diverse purposes and audiences. This research highlights the value of in-situ studies and pathogen monitoring to capture OSS risks in real-world conditions, while also acknowledging the challenges inherent to such assessments, particularly in LMICs.

Finally, the limitations of the research are discussed in terms of scope and methods, followed by a reflection of the implications of this research for policy and practice. There remains potential to apply these methods across different contexts as well as further research to address remaining gaps in understanding and monitoring of health risks of OSSs. The chapter concludes by synthesising the findings and contributions of this research.

7.2 Summary of research

This research aimed to identify and quantify health risks associated with OSSs and examine methods to collect data through monitoring or assessment of health risks, integrating both public health and engineering perspectives of sanitation systems. It sought to address critical gaps in understanding the function and risks of OSSs in LMICs, with a particular focus on pathogen discharges to the environment. Building on prior research on exposure pathways and studies on the health impacts of improved access to sanitation, this research aimed to examine how technical aspects of containment and emptying contribute to pathogen related hazards. The research aimed to generate new data and methods for assessing risk and was guided by the following research questions:

i) To what extent are OSSs implemented in ways that reduce public health risks?
ii) How can monitoring data better reflect risks?

Four studies contributed to investigating these research questions. An initial scoping review confirmed gaps in consideration of health in sanitation decisions and informed the scope of the thesis. This was followed by three empirical studies that assessed key OSS risks through varied assessment methods, considering the interactions between engineering aspects of implementation and the release of pathogens into the environment.

- The first paper included a scoping review of the literature to identify how three potential drivers of citywide sanitation decision-making (public health, sustainability and economic performance) are considered in investment decisions. Through systematic literature searches of academic and high-quality grey literature published between 2015 and 2020, the paper analysed the current state of knowledge about the three drivers, what aspects are critical to differentiate between sanitation options services, and how different drivers are informing sanitation investment decisions. Related to health, the review found significant gaps in understanding of how sanitation failures may spread and cause exposure to faecal contamination and how to select appropriate sanitation solutions to address this. The gaps identified in this research led to the focus of the thesis on the public health driver.
- Paper 2 assessed the direct discharge from septic tanks to drains in a low-income neighbourhood in Dhaka, Bangladesh, and analysed the influence of design, use and operation on pathogen discharge and drain contamination. This research involved the analysis of the presence and concentration of five pathogens *E. coli,* using qPCR and IDEXX, from septic tank effluent and drain samples and used statistical analysis and QMRA to assess the factors affecting concentration and risks of exposure. It found multiple pathogens in all effluent samples with high concentrations and only 1–2 $\log_{10}$ reduction estimated in the septic tank. While

emptying has some improvement on effluent and drain quality, the discharge of septic tank effluent to drains poses significant health risks.

- Paper 3 investigated whether compliance with Indonesia's standards for horizontal and vertical separation between OSSs and wells was associated with reduced faecal contamination. Methods included a census of 112 households in one neighbourhood, surveying and mapping all wells and sanitation facilities with GIS, measuring OSS and groundwater depth, and analysis of repeat well samples for *E. coli* using IDEXX. Repeat measures statistical analysis, controlling for local and environmental factors, found a high presence of *E. coli* in wells. Despite the majority of wells not achieving at least 10m setback from a sanitation system, this horizontal separation was not significantly associated with increased contamination risk. Groundwater depth less than 2m was significantly associated with higher contamination levels, as were other well and environmental factors such as livestock and uncovered dug wells.
- Lastly, Paper 4 evaluated the extent to which consideration of critical exposure pathways through complementary indicators (to global indicators) influenced the assessment of safely managed on-site sanitation and in what contexts or conditions such indicators may be more or less important. A multi-country analysis of survey data from 31,784 households in Asia and Africa was undertaken to evaluate indicators of health risks for local assessments of safely managed sanitation services. The study found that applying additional criteria reduced the population classified as having safely managed sanitation by up to 35%, primarily due to risks like groundwater contamination, animal access, and overdue containment emptying. Nearly three-quarters of on-site systems deemed safe by global indicators were found unsafe when all complementary indicators were applied, highlighting the need for more comprehensive assessments to guide sanitation investments and address local health risks.
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7.3 Discussion of integrated findings

This section synthesises the findings from the four articles, addressing the research questions through five overarching insights. Each subsection references the research articles, compares the findings with previous research, and discusses their implications for reducing health risks associated with sanitation. In response to the **first research**

question "To what extent are OSSs implemented in ways that reduce public health risks?" the findings revealed that many OSSs are not implemented according to design standards or guidelines, discharge high levels of contamination to the environment, and fail to meet criteria for limiting the excreta transmission to humans. In response to the **second research question "How can monitoring data better reflect risks?"** the research underscores the importance of specific local data, given the variation in implementation and risks across contexts, sanitation types, and environments. It also highlights the need for global, national and local data and the value of empirical studies, particularly those examining pathogens and in-situ systems, to better understand and assess risks.

7.3.1 Sub-optimal implementation of OSSs limits health risk reduction

All three empirical studies indicate that many OSS facilities fail to meet implementation criteria in standards, norms or guidelines in contexts such as those covered in this research. Standards or norms are essential for the design, siting, construction, operation and maintenance of OSSs and serve as a basis for assessing implementation. Although no universal standard for septic tanks or pit latrines exists, national or state standards and global guidelines are commonly applied.

The research studies highlight four key OSS implementation issues that are detailed below, including (i) direct discharge of effluent to open drains or surface environment, (ii) OSSs sited close to wells and in shallow groundwater, (iii) OSSs are not regularly emptied, and (iv) many OSSs are oversized in comparison with design and safety guidelines. The compilation of studies in this thesis demonstrates that while these individual issues are not present everywhere, their high occurrence in many locations and the breadth of issues demonstrate a clear problem with how OSSs are currently implemented. This finding is in line with other studies. Issues with non-compliance have previously been reported, including in India, where a multi-state study of 3,000 households found only 2% of septic tanks complied with national standards, and in Ireland, where national inspections found 45% of OSSs assessed were non-compliant (Dasgupta et al., 2021; WHO, 2024). Although included in Paper 4, this section is focused on OSS containments and does not discuss compliance issues with the user interface, such as inadequate slabs, preventing animal access or ventilation, although these are common implementation issues for dry pit latrines (Obeng et al., 2024; Weststrate et al., 2019). The following section outlines these issues, followed by a summary of factors that may contribute to these issues, including communication and the relevance of standards for the context of LMICs.

7.3.1.1 OSSs discharge effluent directly to drains

Effluent discharge to surface environments is a significant concern as tanks and pits alone are expected to provide only minimal treatment of pathogens, and subsurface infiltration is an integral part of the OSS treatment process (WHO, 2018). In the households assessed in Africa and Asia in Paper 4, an outlet to the surface environment occurred for 15% of urban households or 18% of all OSSs. However, the occurrence varied greatly, with 52% of households using improved OSSs with outlets to surface in Bangladesh compared to 1% in the cities assessed in Zambia and 2% in Tanzania. Even within Bangladesh, the prevalence varied between districts, ranging from 12% to 86% between the seven cities assessed. Previous studies of discharge to drain found similar results, with the analysis of faecal waste flow diagrams from 39 cities in Asia and Africa finding that 39% of OSSs were connected to open drains or water bodies, varying from 0% to 75% between cities and much higher in Asian cities than African cities (Peal et al., 2020). Other studies in Asia also reported this was a highly prevalent issue, with between 60% and 92% of OSSs reported to discharge to drains in Bangladesh, Vietnam and India (Dasgupta et al., 2021; Manga et al., 2022; Peal et al., 2020; Ross, Scott, & Joseph, 2016; World Bank, 2015). A recent study from China reported that over 10 million standard three-chamber septic tanks were built in rural China since 2015 without any subsurface infiltration or further treatment of effluent (Tan et al., 2021).

Presence of outlets to drains were influenced by containment type and soil conditions. Analysis in Paper 4 indicated a higher occurrence of outlets discharging to the surface (49%) for systems classified as tanks compared to pits (19% for wet pits, 15% for dry pits). The combined assessment of containment (outlets, overflow and flooding) found that 50% of tanks were uncontained compared with 17%–20% of pit latrines. This aligns with the assumption used in JMP estimates for septic tanks but demonstrates that pit latrines can also be uncontained, whereas the JMP assumes all pits are contained, in the absence of local data (UNICEF and WHO, 2023). From Paper 4, OSSs in soils with low permeability were more likely to have an outlet to surface (37%) than those in high-permeability soils (22%), with twice as many tanks with an outlet to surface in low-permeability soils (60%) compared to those in high-permeability soils (30%). Previous studies report that Dhaka soil is clayey-silt with low permeability and is a likely reason for direct discharge (Ross, Scott, & Joseph, 2016). Studies in the USA have also found many OSSs are situated in unfavourable soil and that soil type was one of the main predictors for septic tank failure (Ravi & Johnson, 2021). Shallow groundwater was not associated with the increased presence of outlets, although saturated soils also likely to limit infiltration capacity. Space and financial constraints for either building a soak pit or installing an overflow pipe to reduce the frequency of emptying were not studied but have been reported elsewhere (Gulati et al., 2020; Williams & Overbo, 2015). The data in Paper 4 did not indicate the presence of outlets differed between wealth quintiles, however, the use of soak pits among households in the two wealthiest quintiles (3%–6%) was greater than in the two poorest quintiles (0%–1%).

7.3.1.2 OSSs do not comply with siting guidelines

Criteria for the design or use of OSSs often include requirements for site locations in relation to other built or environmental factors, particularly to protect groundwater. As detailed in Paper 3, the most common siting criteria is horizontal spacing between wells and sanitation systems, with the three most commonly cited guidelines suggesting 15m spacing (Nenninger et al., 2023). National standards suggest a range of horizontal siting criteria, ranging from 10m in India and Indonesia, 15m in Bangladesh, to 50m in Ghana and Uganda (Parker & Carlier, 2009). In Metro, Indonesia, the analysis in Paper 3 found an average separation from the well to the closest sanitation system was 9.6m, with 60% of OSSs within 10m of the well (Indonesian standard) and 95% within 15m (global criteria). These findings align with other studies in urban areas, such as in India, where 80% of households relying on private wells for potable water had an OSS within 10m, while in peri-urban Mozambique, 58% of latrines were within 15m of wells (Chaúque et al., 2021; Dasgupta et al., 2021).

Although less commonly included in siting guidelines, vertical separation is also important to ensure adequate filtration in unsaturated soils before effluent reaches the groundwater level (Mbae et al., 2023; Nenninger et al., 2023). In Indonesia, national guidelines recommend OSSs with soil infiltration should only be used in areas with more than 2m depth to groundwater, which was not met for 17% of OSSs assessed in Metro, where the average depth to groundwater was 2.9m. Groundwater levels can rise to the base of the containments, limiting the infiltration of liquids from OSSs and, in many cases, resulting in groundwater entering into the containment and a direct connection between the pit and aquifer. Insufficient infiltration depth can occur continuously or only raise during the wet season or following heavy rainfalls. From Paper 3, the groundwater was at or above the base of 16% of containments in Metro, Indonesia. From Paper 4, an average of 10% of improved OSSs reported groundwater at or above the base of the containment, ranging from 0% in the districts assessed in Bhutan, 1% in Indonesia, 20% in Zambia and 24% in Bangladesh.

Aside from the horizontal and vertical separation, some guidelines also consider the soil type in the analysis of groundwater risk from OSSs. In Paper 4, assessment of groundwater risk for urban areas assumed that if wells were in use in urban areas, it was expected that they were within 15m of an OSS. Therefore the analysis of groundwater risk was just based on soil type and groundwater depth, following the matrix from the British Geological Survey Guidelines for Assessing the Risk to Groundwater from On-Site Sanitation (Lawrence & Macdonald, 2001). Paper 4 found that among households with otherwise contained OSSs (i.e. no outlet to surface or overflow), over half (53%) posed a high risk to groundwater. There was significant variation in risk between countries, ranging from 0% in Bhutan to 99% of contained OSSs in Tanzania, as well as within countries, ranging from 0% in Nepal's hilly region to 100% in the low-lying Terai area. While the SDG indicators for containment do not assess groundwater risks, the SFD uses a similar risk matrix yet also considers whether more than 25% of OSSs are within 10m of wells (SFD Promotion Initiative, 2018). A synthesis of SFDs from 39 cities found that 17% of all OSSs posed a significant risk to groundwater, with higher rates in African cities (26%) compared to Asian cities (14%) (Peal et al., 2020). Given both Paper 4 and the Peal et al (2020) studies were not representative national samples, it is not expected that these values are representative of the regions yet demonstrate the potential risk to groundwater yet high variability of this risk.

7.3.1.3 Less frequent emptying and larger size than designed

Many OSS facilities were emptied less frequently than required, often also exceeding the recommended size and emptying intervals outlined in design standards or norms. Standard septic tank designs aim to maintain adequate hydraulic retention time and minimise the discharge of solids that could clog the subsurface infiltration system. This is achieved by selecting design emptying intervals to remove settled sludge, which are often 3–5 years in pre-calculated sizing tables (Mehta et al., 2019; US EPA, 2002). Pit latrines function differently and can either be covered when full and a new pit built or emptied when full, which is more common in urban areas with limited space. The frequency of emptying depends on the pit size and usage. For example, a standard pit (3m deep and 1.5m square) is estimated to take 15 years to fill for a family of six (Reed & Scott, 2014).

Papers 2 and 4 findings indicate that OSSs are generally emptied less frequently than designed, with septic tanks operating well beyond their intended emptying intervals. Of the households assessed in Paper 4, only 20% of OSSs had ever been emptied, with urban areas (22%) showing higher emptying rates than rural areas (6%) and large variations between countries, such as 32% of assessed OSSs previously emptied in Bangladesh yet only 1% in Zambia. Comparable findings were reported in other studies, including an average of 39% of OSSs were previously emptied in the analysis of SFDs from 39 cities in Asia and Africa and 0.2%–18% of pit latrines emptied in rural areas supported by the Global Sanitation Fund (Conaway et al., 2023; Peal et al., 2020; Robinson & Peal, 2020). In Paper 4, pit latrines were typically emptied between 8 to 15 years post-construction, whereas septic tanks were emptied on average more than 20 years after construction. Long operation times have also been reported in other studies (e.g. up to 23 years in Asia and 30 years in Sub-Saharan Africa), yet these studies also reported more frequent emptying (1 to 4 years), which was not found in the households assessed in this thesis (Conaway et al., 2023; Moonkawin et al., 2023; Nakagiri et al., 2015).

Infrequent emptying can lead to operational inefficiencies, reduced function and increased environmental and public health risks. Extended storage and delayed maintenance increase the discharge of untreated solids, contributing to environmental pollution and health hazards. Recognising this, Paper 4 proposed assessing OSS safety based on whether a system was overdue for emptying. Since OSSs vary in size and function, a universal emptying frequency cannot be applied. Instead, a “timely emptying threshold” was proposed, tailored to local contexts considering containment type, size, sludge accumulation, and inflows. Analysis in Paper 4 indicated that 67% of respondents used improved OSSs that had never been emptied, and one-third of these systems had operated beyond the timely threshold. Operating beyond the timely threshold occurred for both tanks and pits. It was more common in urban areas, with 30% of urban respondents using an OSS not emptied within a timely frequency, compared with 18% in rural areas.

While global monitoring is only concerned with whether an OSS has ever been emptied, evaluating OSS safety against this threshold provides insight into potential hazards from overflows or malfunctions and helps anticipate future emptying demand. These methods could be refined with improved local data on containment size and sludge accumulation for different OSS types. In addition, there has been limited research on the health risks of overdue storage or regular emptying on public health (Conaway et al., 2023). Paper 2 indicated that septic tanks beyond the emptying threshold (with more than two-thirds sludge volume) had higher pathogen concentrations in effluent and associated drains compared with those operating within design standards. The pathogen concentration in the one emptied tank were lower than other tanks of a similar age, however only one tank had been emptied.

Containment size and emptying frequency are interrelated design criteria, and data from Papers 2 and 4 suggest that many OSSs are oversized compared with design standards. Design standards from HICs for septic tanks typically recommend a depth of 1.5m, width of 1m–1.5m and length of 2m–2.5m with volumes sized from $2m^3$–$6m^3$ for two to ten users (AS/NZS, 2012; US EPA, 2002). Pits are typically recommended to be 2.5m–4m deep and 1m–1.5m wide with volumes of $5m^3$–$10m^3$ for use for five to ten people and 5 to 10 years (WEDC, 2014). Households surveyed for Paper 4 reported a wide range of OSS depths, with the average in most countries from 2m–3m, yet much deeper systems were reported in Bangladesh (8m) and Tanzania (12m) (Supplementary Tables 5–7, see Appendix C). The average containment size suggested by SNV staff also varied, with septic tank volumes ranging from $1.3m^3$ to $8.3m^3$ and pits from $1.3m^3$ to $5.6m^3$. Although it is expected that households may have overestimated the depth, and it is questionable whether pits could be built more than 10m deep without collapse, local SNV staff in Tanzania confirmed pits were typically around 8m deep. Other studies have also found varied OSS sizes, including a range of $0.7m^3$ to $9m^3$ for pit latrines in rural areas of 11 countries supported by the Global Sanitation Fund, while in India, a study found 94% of septic tanks were larger than design standards (Dasgupta et al., 2021; Robinson & Peal, 2020).

Further information and training could support engineers and masons sizing OSSs based on the availability of emptying services for regular emptying with challenges of collapse and difficulty emptying oversized pits and tanks. Additionally, whether a wet pit or septic tank receives greywater is another critical factor in sizing OSSs. As noted in Paper 2, most septic tank standards, often based on HICs, assume tanks receive both blackwater and greywater flows, meaning they are substantially oversized if only blackwater flows are connected. Considering hydraulic loading, smaller tanks could be appropriate for blackwater flows only. However, given the concentration of pathogens and solids is higher in blackwater, the additional retention time of oversized tanks and the infrequent emptying could mean larger tanks are needed to achieve the same treatment outcomes. Further consideration of inflows in septic tank design and research on septic tank sizing for blackwater-only tanks is needed.

7.3.1.4 Factors contributing to poor implementation

The widespread failures in OSS implementation summarised above underscore the need for improved strategies to improve design, siting, maintenance, and user awareness of standards and best practices. This section reviews possible causes for poor implementation, considering physical factors and how standards or norms are implemented and communicated.

Physical factors are a clear reason why some of these implementation issues occur. The findings from Paper 4 indicated that impermeable soils were associated with an increased risk of outlets to the surface environment; and although shallow groundwater was not found to increase the risk of outlets, it could reduce infiltration capacity. Although not investigated, reduced infiltration and construction of outlets could also occur if soils are clogged after long-term use of pit latrines or septic tank soak pits, particularly if households want to avoid regular emptying. Another physical factor is limited space in many dense urban areas which restricts the size of containments, space for a soak pit or leach field, and limits the possibility of rebuilding a pit latrine once full. Physical access to emptying services may be limited due to OSSs being covered or inaccessible, narrow access in dense informal urban areas, and a lack of service availability in many urban areas. Construction and emptying costs may also influence design or operation, and while lower-income households were more at risk of OSSs with animal access and uncontained systems, their systems were less likely to be overdue for emptying than higher income households. These physical issues and constraints are also mentioned in other literature (Conaway et al., 2023; Gwenzi et al., 2023; Strande et al., 2023).

Non-compliance with standards or norms can occur for various reasons, including poor communication and awareness of standards, lack of enforcement or absence of standards relevant to the systems used (ISF-UTS, 2017). OSSs are often poorly regulated, with the responsibility predominately on households and enforcement of standards such as through building inspections are either not done or inadequate to detect defaults (Hashimoto, 2021; Weststrate et al., 2019). Promoting adherence to standards through stricter regulatory oversight, capacity building for masons and development partners, and community education is essential. In Mozambique, regulation of on-site sanitation in low-income high-density areas of Maputo was limited due to a lack of standards for pit latrines, inappropriate construction and emptying standards for low-income areas, and the inability of households to afford to comply with standards (Weststrate et al., 2019). OSS regulations are often only applied at the time of construction. However, ongoing inspections are important to identify post-construction management issues, such as lack of emptying or connection to drains. Regular inspections of OSSs are conducted in Ireland, France and Japan as part of water and environmental protection legislation but this requires a strong regulatory environment and is not common in LMICs (WHO, 2024). Lastly, standards may need to be adapted to suit local conditions rather than applying those from HICs. However, adapting standards requires a sound understanding of the basis of design, local conditions and risks. For example, in India, the septic tank standard has not been updated since the 1980s and does not align with current practices and issues (Dasgupta et al., 2021).

Poor communication of OSS design standards and public health risks, particularly related to effluent management, is another potential cause for poor implementation of OSSs. The absence of subsurface infiltration systems may be influenced by most OSS service chain diagrams or septic tank drawings not including effluent management (i.e. leach field or soak pits). Figure 7.1 shows commonly published sanitation service chain diagrams, which focus on the sludge stream and do not show the need for management of effluent after the septic tank (BMGF, 2012; WaterAid, 2022). The septic tank design drawings used for the construction of the septic tanks assessed in Dhaka in Paper 2 only included the tank and no design or indication of the need for a soil infiltration system. In Figure 7.2, I present an updated service chain drawing for OSSs that indicates the importance of management of both liquid and solid streams at the OSS as well as in faecal sludge treatment, which is required for safe treatment for SDG 6.2. The term ‘septic tank’ is commonly used in WASH discourse to refer to a range of OSSs including various pit latrines, cesspools and tanks (Peal et al., 2020; Strande et al., 2023). Whereas literature from HICs more commonly uses the language of ‘septic tank system’ which may be more appropriate to demonstrate that a septic tank system is more than just a tank (Geary & Lucas, 2019; Richards et al., 2016b). Given that OSS refers to a broad range of systems with different risk and operation requirements, greater clarity around terminology could also improve understanding and management of risk and is discussed further in Section 7.3.3 in relation to monitoring.

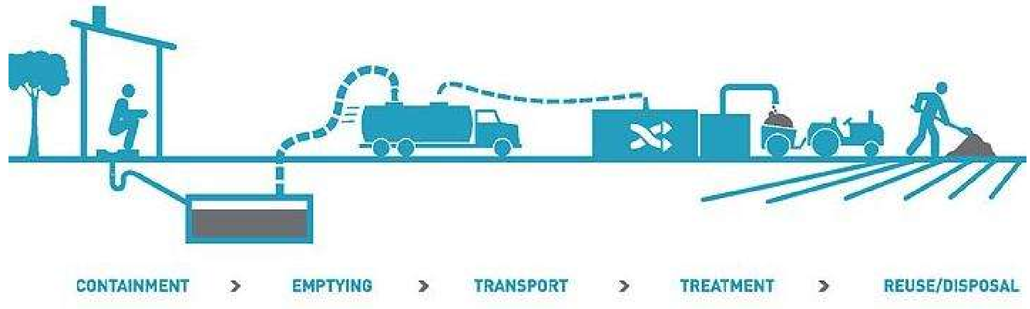

Figure 7.1 *Widely used sanitation service chain diagram: Initially published by Gates foundation (BMGF, 2012; WaterAid, 2022)*

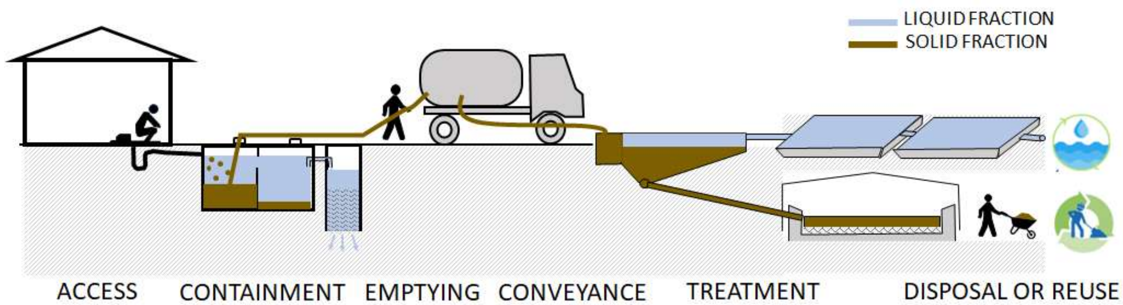

Figure 7.2 *Alternative on-site sanitation service chain for septic tank systems that indicates both solid and liquid streams*

7.3.2 OSSs as currently implemented are associated with multiple health risks

The previous section demonstrated that many OSSs are not implemented according to standards and this section summarises the risks associated with current OSS practices. The findings demonstrate that OSSs are discharging high levels of contamination to the environment and failing on many criteria to limit the transmission of excreta to humans. It is evident that addressing health risks from OSSs remains a priority issue for LMICs and these findings question their suitability in certain contexts and considering their current implementation. I first present the combined risks related to OSS containment and emptying, followed by an in-depth discussion on the risks associated with outlets to drains, groundwater contamination and infrequent emptying.

7.3.2.1 “Safely managed” OSSs, as per the SDG definition, continue to pose health risks

The SDG indicator for sanitation of safely managed services is a major improvement on the approach used in MDG monitoring, and achieving 100% access to safely managed services remains an ambitious target for many countries. Despite this, the monitoring of SDG 6.2.1 only includes a limited number of indicators, and many aspects related to health are excluded from the global assessment of “safely managed sanitation”. While other elements of SDG monitoring have been debated and researched, such as the assessment of shared sanitation systems (Evans et al., 2017; Schelbert et al., 2020) and the indicators for safely managed water supply (Charles et al., 2020), there are only a few papers that discuss the definition and monitoring of safely managed sanitation services. A forum paper noted the lack of discussion on how safely managed wastewater and faecal sludge are defined and argues for the consideration of social perceptions of safety and the value of pathogen data to assess risk (Rose et al., 2019). Beard et al (2022) highlight the limitations of global monitoring for assessing sanitation in urban areas of LICs but focused on definitions of improved facilities, while in Austria, complementary indicators were proposed for locally relevant analysis of safely managed sanitation, but these focused on sewers in HICs (Beard et al., 2022; Germann & Langergrabe, 2022) rather than OSSs.

The analysis in Paper 4 found almost 75% of systems classified as safely managed based on the global indicators in fact presented multiple risks to public health when considering four additional complementary indicators of animal access, groundwater risk, infrequent emptying and unsafe OHS during emptying. Other health risks during transport, treatment and disposal are also likely although were not assessed. While alternative sanitation options such as sewerage were not assessed, the findings indicate that the safety of OSS services is overestimated and that positive health outcomes may not be achieved unless we aim for a more a higher standard of service. These findings highlight the need to think beyond the global assessment of ‘safely managed’, as well as the need to radically improve how OSSs are designed, constructed and operated so that they protect against the spread of faecal-related diseases and public health risks.

7.3.2.2 The high release of pathogens into drains is a concern

As septic tanks are not intended to discharge to the surface environment and are designed principally based on physical treatment parameters (i.e. TSS and BOD), there have been few studies on the concentration of pathogens discharged from septic tanks. Paper 2 presented new findings on the discharge of pathogens from septic tanks, with all septic tank samples positive for one or more pathogens, ranging from 17% of samples positive for *Giardia* and 94% positive for *Shigella*. The concentrations of pathogens in effluent ranged from 4.2–5.6 log_{10} GC/100mL for pathogens and 7.6 log_{10} MPN/100mL for *E. coli*. These findings are slightly higher but in the range of *E. coli* concentrations observed in septic tank effluent in India of 6–6.9 log_{10} MPN/100mL, also for two-chamber blackwater-only tanks (Manga et al., 2022). Other studies found *E. coli* concentrations of 4.9–7.15 log_{10} MPN/100mL in the effluent from septic tanks receiving both greywater and blackwater flows, which aligned with the equivalent combined discharge from Dhaka of 6.4 log_{10} MPN/100mL (Buchanan et al., 2018; Humphrey et al., 2011; Lowe, 2009; Pang et al., 2004; Richards et al., 2016b). Although concentrations were not reported, a study of effluent from three-chamber septic tanks in China found no significant difference in the number of species, abundance or diversity of pathogens between the influent and effluent, with high levels of antibiotic resistance genes (Tan et al., 2021). Data on other pathogens discharged from septic tanks were only available from one study from the USA for *Giardia* and one study from India for *Shigella*, highlighting the novelty of this study.

The study also provided new data on the high concentrations of pathogens in open drains, with most previous studies in LICs measuring only *E. coli* concentrations. The majority (70%) of the Dhaka study site used toilets that directly discharged to drains, resulting in a higher presence of pathogens in drain samples than septic tank effluent and concentrations ranging from 3.1–5.8 log_{10} GC/100mL pathogens and 7.7 MPN/100mL log_{10} *E. coli* in the combined drain flows in the dry season. These concentrations were within the range of *E. coli* concentrations of 5–8 log_{10} MPN/100mL found in various low-income urban areas assessed through the SaniPath project (Y. Wang et al., 2022), as well as concentrations found in drains in Accra, Ghana (4.1–8.5 log_{10} CFU/100mL) (Berendes et al., 2018, 2020). While various studies have assessed pathogen concentrations in wastewater, analysis of pathogens in open drains is less common. In Accra, Norovirus GII was detected in 6%–13% of drain samples, much lower than the 67% presence in open drains in Dhaka (67%), but did not measure virus concentrations although the authors recommend that concentrations of enteric viruses in the environment would be valuable to improve understanding of sanitation risks (Berendes et al., 2018).

This high presence and concentration of pathogens in septic tank effluent and in drains is a concern given exposure to drains has been found by many studies to be a major transmission pathway for faecal pathogens, particularly for low-income urban areas (Coulibaly et al., 2023; Medgyesi et al., 2019; Y. Wang et al., 2022). Paper 2 found some benefit in the use of septic tanks over direct discharge, with a 10% increase in the use of septic tanks significantly associated with a 0.1–0.3 $\log_{10}$ GC/100mL reduction in *Shigella* in drains and an estimated 1.7–2.2 $\log_{10}$ GC reduction of pathogens in the tank. However, this reduction and the discharge of septic tank effluent to drains without further treatment is insufficient to protect public health. The potential risk of illness using a QMRA approach estimated that even if the entire study area used septic tanks, exposure to septic tank effluent could result in illness of 18,000 and 3,000 children per 100,000 per year from Norovirus GII and *Giardia,* respectively, assuming 1mL of drain water is ingested by children up to 14 times per year. These findings question the value of investing in septic tanks discharging to drains unless additional infrastructure is provided to safely transport and further treat effluent, for example, a piped effluent sewer to decentralised treatment (Foster, Falletta, et al., 2021). These findings highlight the importance of ensuring subsurface effluent infiltration from OSSs where feasible and otherwise integrating additional effluent management and treatment solutions to mitigate health hazards.

7.3.2.3 Sanitation is one of many potential groundwater contamination pathways

While the health risks of contaminated drinking water supplies are evident, the findings were inconclusive in the role of OSSs in contamination. The studies explored this relationship through different methods, with Paper 4 applying standard matrices and assumptions to classify risk and Paper 3 testing siting criteria at a site with shallow groundwater. These studies also highlight the interactions between water and sanitation systems and the challenges in identifying the causes of contamination when neither system is ideal or safe.

Risk matrices are widely used to assess potential groundwater contamination and Paper 4 applied a matrix from literature that combined soil type and groundwater depth to evaluate whether OSSs posed a high or low risk to groundwater (Graham & Polizzotto, 2013). Among households with otherwise contained OSSs (i.e. no outlet to surface or overflow), over half (53%) posed a high risk to groundwater. However, the health risks associated with groundwater contamination also need to consider exposure, therefore whether households use groundwater for drinking water supplies. Beyond SNV's monitoring approach, Paper 4 also included an assessment of risk considering groundwater use, with the assumption that groundwater contamination is only considered a high risk where 25% or more of the surveyed population used groundwater for drinking. This adjustment reduced the assessed risk of contained OSSs posing a risk to groundwater from 53% to 36% when use was considered. The main reduction occurred in the Tanzanian cities, where the potential risk to groundwater was high but groundwater use for drinking was uncommon. However, this raises a critical debate: should groundwater contamination risks be considered acceptable if groundwater is not currently a primary drinking water source for domestic use? While groundwater is the main drinking water source in Southeast Asia and the Pacific, as well as parts of Latin America and Sub-Saharan Africa, its use as a secondary supply, such as during piped water outages or an alternative to bottled supply, is often underreported (Carrard et al., 2019; Foster, Priadi, et al., 2021). Household wells are likely to remain an important source of water for households without access to piped supplies, in informal areas for those unable to afford water tariffs, and during shortages to surface supplies as are expected to increase with urbanisation and climate change (UN Water, 2022). In many regions, it is therefore essential to protect groundwater quality for vulnerable populations and future generations.

While the proximity of OSSs is a commonly attributed cause of faecal contamination of wells, there are also many other possible sources of well contamination. Despite the widespread use of well separation guidelines as a means to reduce the risk of OSSs contaminating wells, Paper 3 found no significant association between sanitation proximity factors and well contamination. Groundwater in the study area posed a high risk to public health risk, with *E. coli* detected in 61% of wells, including in 71% of dug wells and in 30% of boreholes, with 26% of wells with concentrations greater than 100 MPN/100mL. Most OSSs in the study area did not comply with Indonesia’s siting guidelines, with 61% of wells located within 10m of an OSS and 13%–22% in groundwater less than 2m deep. However, statistical analysis identified that only well type and cover, and depth to groundwater were significantly associated with the presence of *E. coli* and high contamination levels in wells, while the presence of livestock near the well was also significantly associated with high contamination levels (above 100 MPN/100mL). Shallow groundwater was associated with higher contamination levels. Given the average infiltration depth between the base of the OSS and groundwater was 0.8m, it is feasible that OSSs contribute to shallow groundwater contamination, although it was not proven at this site and with these methods. At the same time, there are multiple other possible pathways for shallow groundwater contamination, such as livestock, unlined ponds or uncovered wells.

These findings do not rule out OSSs as a contributing factor to well contamination but suggest that inadequate well infrastructure and local contamination pathways play a more dominant role. Studies have identified stronger associations between well contamination and factors such as well type (unimproved or unprotected), well construction, and presence of animals rather than sanitation proximity (Fejfar et al., 2024; Odagiri et al., 2016; Ravenscroft et al., 2017). Increased contamination in shallow groundwater has been reported in various studies, with some studies attributing this to sanitation due to the reduced infiltration depth below OSS increasing the risk of pathogens reaching groundwater as well as their horizontal travel distance (Mbae et al., 2023).

While some studies critique the rapid increase in the use of OSSs for exacerbating well contamination (Daniels et al., 2016; Templeton, 2015), the findings from Paper 3 align more with the findings from studies that suggest OSSs may have less influence on well quality than other pathways and improvements should prioritise well infrastructure and management (Ravenscroft et al., 2017). Despite this, these findings do not rule out OSSs as a contributing factor or dispute the studies that have found an association. High contamination levels and dominant alternative pathways may obscure sanitation-related impacts at this site. Additionally, limited variation in sanitation factors, such as setback distances and groundwater depths, may constrain the detection of significant effects. Despite efforts to control confounding variables through census data, repeat sampling, and physical measurements, real-world conditions, including the presence of uncovered wells and animal access, posed challenges to isolating OSS influences. The future research section (7.5.3) outlines approaches to improve analysis of the role of OSSs on contamination, including the importance of differentiating animal and human faecal sources.

The findings from Paper 2 raise questions about the suitability of the matrix approach used in Paper 4 to assess complementary indicators on the safety of OSSs for groundwater. Monitoring for global or national purposes and local planning requires varied levels of detail. While assumptions about the potential risk to groundwater may be suitable for a high-level assessment of critical risks, one-size-fits-all siting guidelines and matrices are less suitable for informing planning and sanitation decisions in regions like Indonesia, where use of OSSs and household wells is prevalent, and geographic conditions vary. For sub-national planning and investment decisions, local risk assessments, supported by modelling may be more appropriate to identify and mitigate priority risks in dense urban areas, particularly with shallow groundwater (Mbae et al., 2023; Nenninger et al., 2023). In contrast, modelling and detailed risk assessment may be less suitable for national or global scale monitoring given the complexity and variability of pathways and risks. However, increased local modelling and research could provide insights to improve or validate the current matrix-based approaches for different contexts. Given climate change is likely to increase water scarcity in many regions, while at the same time heavy rainfall may increase groundwater levels, protecting groundwater from contamination should remain a public health priority, and requires an integrated approach to risk assessment and water and sanitation planning.

7.3.2.4 To empty or not to empty – a balance of risk

Regular emptying of OSSs enhances functionality, particularly for septic tanks, but often leads to improper sludge disposal, creating new environmental and public health risks. For pit latrines, which function differently from septic tanks, emptying is often necessary for continued use, particularly in dense urban areas. However, unsafe emptying methods and the risk of unsafe disposal, including manual handling without proper protective equipment, further exacerbate health hazards. Paper 4 found that 70% of emptying occurred without adequate PPE (i.e. mask, gloves, boots) and 20% involved someone entering the pit to empty manually. Not wearing PPE was common practice in several studies (Conaway et al., 2023), with a review of sanitation worker practices in Africa indicating that impracticality and unavailability of PPE were key reasons for low use (Philippe et al., 2022). Entering the pit is also commonly reported but not quantified; however many studies have investigated technologies to empty dry pits without emptying (World Bank, ILO, et al., 2019). Other studies have found that in many LMICs, emptied sludge is often released untreated to the environment, including the review of 39 cities in Africa and Asia found that only 35% of emptied sludge was taken to treatment facilities (Peal et al., 2020). A systematic review of faecal sludge emptying literature found 22 papers indicating faecal sludge was dumped off-site in the environment and six studies indicating it was disposed of in the household environment (Conaway et al., 2023). These findings highlight a range of issues with exposure to pathogens during emptying and disposal that affect both sanitation workers and the general public.

The risks associated with unsafe emptying and disposal must be weighed against the risks of not emptying, considering how the local context, availability and quality of emptying services affect these risks. Infrequent emptying may lead to issues like overflow, backflow, clogging of leach fields, solidification of sludge and risk of inability to use the toilet, although research on these risks is limited. Paper 4 indicated containment issues, including flooding and overflow were a greater risk for older and larger OSSs. While oversized OSSs may allow increased storage time, they also increase the risk of collapse during construction or emptying. In rural areas, some authors suggest that not emptying pits and leaving sludge buried may be a lower risk to public health than poorly managed emptied sludge (Robinson & Peal, 2020). In contrast, others argue that it cannot be assumed all 400 million pits in rural areas will be rebuilt once full, and while storage in-situ may be the safest solution now, there is a risk of reverting to open defecation and therefore emptying, transport and disposal services also need to be developed in rural areas (Greene et al., 2021). Promoting the use of PPE and emptying technologies that avoid entering are essential steps towards safer sanitation practices, although increasing research indicates that these must adapt to the needs and preferences of workers (Philippe et al., 2022). Sustainable solutions must balance immediate containment needs with long-term goals of developing robust and safe emptying, transport, and treatment services to meet the demands of both urban and rural settings.

7.3.3 Variable implementation and risks require local data

The implementation and risks associated with OSSs vary significantly by location, underscoring the need for context-specific data to guide sanitation investments. This section first summarises the findings on the extent different risks occurred in different locations or due to different sanitation types or contextual factors, which respond to the first research question. This is followed by a discussion on how this variability demonstrates the value of local data and the limitations of generic labels for OSSs, which contributes to the second research question.

The findings from Paper 4 demonstrated different critical risks between and within countries, as well as variations in risk for the same technology depending on context and use. Figure 7.3 shows the variation in the impact of different complementary indicators between countries. For example, in rural Bhutan, animal access caused the greatest reduction in the proportion of OSSs considered safely managed. In contrast, animal access had a minor impact in rural Laos, yet risk to groundwater and overdue for emptying were important. Within countries, variabilities were also evident in the city and district data shown in the supplementary figures, which were often associated with the varied geophysical contexts within countries, such as the differences in risks in the low-lying Terai region and the hilly mountain regions of Nepal. This variability is also evident in the literature analysing SFDs, which found different failure modes were critical for different cities and authors noting that "every city has its specific sanitation characteristics" (p12, Peal et al., 2020). Comparison of SaniPath findings between 45 neighbourhoods in nine countries also found dominant exposure pathways varied within cities and between countries and reinforced the need for context-specific interventions (Y. Wang et al., 2022). Research disaggregating the progress of water and sanitation SDGs at a sub-national level also found heterogeneity and that national data often masks local trends (Quispe-Coica & Pérez-Foguet, 2022).

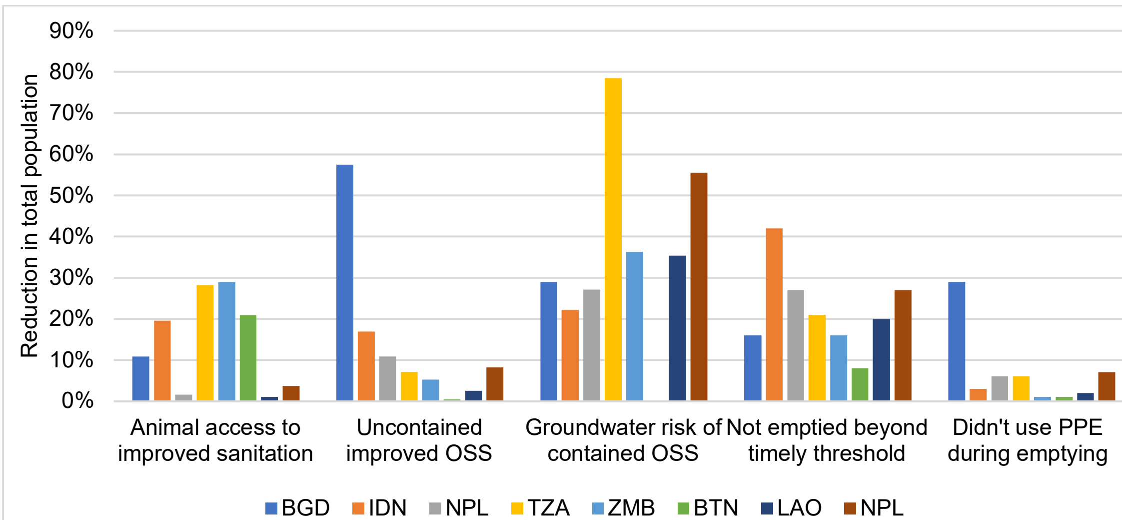

Figure 7.3 *Variation in the impact of different indicators between countries demonstrates that a major risk for one country may not be an issue for another*

The sanitation infrastructure, how it is implemented, and the context in which it is situated also influence the risks. Therefore, generalisations that specific sanitation systems are safer should also be avoided. For example, dry toilets had a higher risk of animal access (65% access) than flush toilets (15%). However, both dry and wet pits had a similarly lower risk of having an outlet to the environment (18%) compared with septic tanks (50%). As noted above, OSSs in low-permeability groundwater were more likely to have outlets than those in high-permeability soil, although this did not differ with groundwater depth. Temporal changes also affect OSS risks and system functionality. For example, OSSs reliant on soil infiltration may operate well during the dry season but could fill and overflow in periods of high groundwater or over time as the soil becomes clogged. Households may resort to unsustainable practices if their systems change over time, such as creating outlets to drains to avoid frequent emptying costs, as demonstrated by the findings from Paper 4 that showed systems with outlets were more likely to have previously been emptied. There has been limited discussion of the variations in risks for different sanitation systems, either due to studies focused on one type of sanitation, (i.e. pit latrines) (Gwenzi et al., 2023), and studies often do not clearly define the type of systems assessed (Nasim et al., 2022; Nenninger et al., 2023).

These variabilities highlight the importance of monitoring data that can reflect how OSSs are implemented and function within that local context and any changes over time. Monitoring and reporting national or urban/rural averages will be insufficient to identify local variabilities and priorities, therefore sub-national monitoring systems need strengthening (Quispe-Coica & Pérez-Foguet, 2022). Sub-national data can be extracted from national surveys if the sample size is adequate. While household surveys can capture data related to access, containment and emptying, additional data sources are required for transport, disposal and treatment, yet administrative or service provider data is rarely available for OSS services (UNICEF and WHO, 2023). The complementary indicators proposed in Paper 4 can provide further information to assess risks compared with the core JMP questions. However, as discussed in Paper 4, not all complementary indicators will be required in every context. Where background information is available, the questionnaires can be optimised to suit national or sub-national contexts.

Beyond the complementary indicators, this research has also highlighted that generic OSS labels may be less useful for assessing risks compared to assessing key features of infrastructure or environmental features. It is increasingly evident that 'septic tank' and 'pit latrine' are used and interpreted inconsistently, affecting data accuracy (Strande et al., 2023). From this research, the following aspects are valuable for understanding the function and risks of OSS: (i) inflows to the toilet (flushing, dry, solids or waste, greywater), (ii) containment more of a permeable pit or semi-sealed tank (recognising that lining and permeability is challenging to discern from the surface), (iii) presence of an outlet and discharge location, (iv) other events that release excreta to the surface (flood, overflow, damage), (v) access by animals or insects to excreta (i.e. pit covering, slab, cracks, vents), (vi) previous emptying and age, (vii) safety when emptying, and (viii) disposal of emptied excreta (households can only report if disposed of in-situ, nearby into the surface or taken off-site). Recent papers have also highlighted the importance of improving definitions of OSSs, including the standard categories present in a study in India (Manga et al., 2022) and categories of sanitation storage and transport (Strande et al., 2023), although the second paper focuses on ideal systems only and for correct classification and assessment non-standard or unsafe systems also require clear labelling.

Monitoring sanitation often requires sources beyond household surveys, including inspections, key informant data or secondary data sources. While soil type, depth to groundwater, depth of containment and containment volume were used in the analysis in Paper 4, it is expected that self-reporting this data has low accuracy and may be best sourced from interviews, secondary data (for hydrogeological features) or a select number of inspections. Inspections during emptying would be beneficial to assess permeability, type of containment, depth and volume. Inspections can validate household responses or conduct preliminary risk assessments to inform the prioritisation of questions for the household surveys. Inspections are also used to regularly monitor OSS status and risks, such as in Ireland and France as part of environmental protection and service delivery laws (WHO, 2024). Although beyond the scope of this thesis, monitoring transport, treatment and disposal requires data from service providers, service authorities or regulators, yet globally little administrative data exists on OSSs and management of faecal sludge (UNICEF and WHO, 2023).

7.3.4 Different specificity of data needed for different scales

Understanding risks and informing sanitation investments benefits from data from a range of scales, including high-level global monitoring, context-specific local indicators and detailed empirical studies on specific pathways or contexts. By monitoring at various levels, we can gain a better understanding of different types of risks, also recognising that different actors or decisions require different levels specificity or disaggregation of data. For example, global monitoring relies on regression of national data over time and assumptions to fill data gaps for comparing the overall status of sanitation status between countries. Whereas a municipal engineer needs data on the current infrastructure in certain neighbourhoods at a local scale to plan specific sanitation improvements. Lastly, detailed empirical studies are valuable for improving understanding of how OSSs function and the number of pathogens discharged but are often specific to that context or containment types. This section responds to the second research questions and discusses how OSS risks can be assessed at different levels in terms of what data are collected, what methods are suitable and how these data can contribute to improved understanding of risk.

7.3.4.1 Global monitoring

Global monitoring provides a representative analysis of the general status of sanitation enabling comparison between countries and over time, rather than in-depth analysis of specific issues. The estimates reported by the JMP are based on nationally representative data, either available publicly or shared during country consultations (UNICEF and WHO, 2023). For sanitation, these data are predominately from household surveys and censuses, which can assess aspects of access, containment and emptying, as well as administrative data often on sewerage systems and treatment. The last JMP report only included estimates of emptying and treatment of excreta from OSSs from five high-income countries, highlighting the major gaps in data for the entire OSS service chain (JMP, 2023). Where there are data gaps, assumptions are used to complete estimates, such as applying wastewater data in countries where sewers are the main sanitation type, or assumptions on containment and emptying based on the classification of septic tank or pit latrine. While useful for completing regional or global estimates, these assumptions somewhat mask the data gaps and may be overestimating the safety of OSS services. Another challenge of limited data is that global estimates and indicators are used beyond their intended purpose given they are often the only available data on OSS services.

How can global monitoring better reflect risks?

The SDG indicators represent significant progress in assessing sanitation compared to the MDGs but fail to capture critical health risks, such as groundwater contamination, emptying frequency, and the safety of sanitation workers. While prior literature has called for better indicators (Beard et al., 2022; Kempster & Hueso, 2018), Paper 4 adds a practical dimension by illustrating how additional risks can be assessed and incorporated into household surveys. As noted in Paper 4, integrating complementary indicators could significantly refine the estimates of safely managed services, though their adoption in global monitoring is constrained by data availability, standardisation challenges and limited resourcing. This research also aims to improve awareness of the risks global monitoring does and does not include, so users of global data understand what the estimates represent, and countries could adopt these indicators or other locally relevant measures to address the global monitoring gaps. National acceptance of risk differs, as do the pathways to safely managed services. Therefore, countries should select indicators and targets relevant to their context. Many countries have debated whether the global approach to excluding shared sanitation facilities is suitable for their national context and sanitation development priorities (Evans et al., 2017; Sprouse et al., 2024). Some countries are beginning to discuss whether to adopt a local definition of containment that considers groundwater risk or emptying rather than frequency.

Improved global monitoring relies on improving national monitoring systems and data that can align with standardised definitions and indicators. Harmonised definitions of sanitation systems are needed for improved comparability and assessment of risk, with standardised surveys such as UNICEF's MICS survey including core questions and response categories that clearly differentiate sanitation facility types and assessment of containment, emptying and disposal. Greater awareness of national authorities of how different assumptions apply to containment types and how the SDG indicators are assessed can drive improved data collection. Awareness of the assumptions recently improved national data collection approaches in Cambodia and Bangladesh, where containment types that were previously misclassified led to incorrect estimates of safely managed sanitation, resulting in the implementation of national sanitation inspections and an improved national census to improve toilet classification (WHO, 2024). Further research could clarify the accuracy of the assumptions, such as pit latrines should be classified as 100% contained, although it is unlikely that these will be updated in global estimates in this SDG period.

Moving forward, there is increasing interest in monitoring risks associated with climate change and WASH, as well as the use of emerging remote monitoring technologies. With climate-resilient water supply and sanitation included in global climate adaptation targets, there are currently projects developing definitions and indicators to monitor climate-resilient WASH. The role of sanitation in protecting public health needs to remain central to discussions on climate impacts, resilience and adaptation. New technologies, such as Earth observation and remote sensors, offer promising tools to monitor sanitation health risks as well as climate-related risks (Rary et al., 2020; Shah et al., 2023). Examples of application include the use of global SDG data and open source spatial data to create visual maps of sanitation risk or pathogen hazards (Okaali et al., 2019; Sultana et al., 2023). There remain many opportunities to optimise emerging technologies for global monitoring or risk assessment that are valuable for increasing awareness and engagement with sanitation-related risks. However, it is important they clearly state the assumptions and uncertainties used to avoid misinterpretation.

7.3.4.2 National and sub-national monitoring and assessment

Generalised global or national data often hides local variabilities, as noted above. Local health risk data is essential for informed sanitation investment decisions, helping prioritise risks, identify affected areas, and address underlying issues. This data could come from local surveys or national censuses that regularly monitor the key sanitation and context features discussed in the previous section and the relevant complementary indicators presented in Paper 4. A recent UN-Habitat report emphasised the urgent need to strengthen city- and country-level monitoring systems, as current investments often lack the data necessary for effective planning, management and addressing inequalities (UN-Habitat, 2023). National data is valuable to understand the status of sanitation and systemic issues that could be addressed by policies and standards, as well as to identify which regions require priority investment or actions. However, national data often masks the sub-national trends and sampling or analysis might be inadequate for a detailed assessment of individual cities (Quispe-Coica & Pérez-Foguet, 2022). Sub-national or city-level data is needed to inform investment planning, identify inequalities, and, if regularly collected, can track progress, regress, and more immediately address potential health risks, such as treatment plant failures or illegal discharges. The need for data to inform planning is identified in both the CWIS framework and the WHO and UNICEF steps to achieve safely managed sanitation (Schrecongost et al., 2020; WHO & UNICEF, 2024).

Strengthening national and sub-national monitoring to better assess risk

National and local data collection can better assess health risks by first ensuring that OSS data is collected along the entire sanitation service chain, supplemented by additional indicators tailored to local contexts. Standardised indicators from programs like MICS or JMP provide a clear baseline of data and may require harmonising current local definitions. As discussed in Paper 4, complementary indicators that align with national targets or locally identified risks should also be assessed, with Paper 4 providing some indication of what contexts particular issues may be more prevalent. While not included in this thesis, risks during transport, disposal, and treatment, such as spillage or inadequate disposal practices, should also be monitored. Establishing appropriate indicators involves reviewing existing data, conducting baseline assessments, and setting targets and systems for ongoing monitoring.

Demand for and use of this data often drives improved monitoring systems that enable data use to inform decisions. Tools like excreta flow diagrams (SFDs) and sanitation safety planning can initiate semi-qualitative data collection and highlight service and data gaps. Authorities should regularly monitor their services against outcomes, however, service data is less commonly available for OSSs compared with sewer systems. Standardised monitoring of service provision is under development. For example, NWASCO, the sanitation regulator in Zambia, has developed spatial mapping and inspection of household OSSs that will inform both the delivery of emptying services and the status of OSSs for regulator reporting (WHO, 2024). In other countries such as Indonesia and Bangladesh, local governments or service providers have created GIS databases of OSSs as an initial step towards implementing scheduled emptying services. Geo-referenced data can effectively identify pollution hotspots such as clusters of poorly contained OSSs or gaps in access to basic services, as well as accessibility for safe emptying services (Gwenzi et al., 2023). National data systems and support to cities to collect, report and use data are necessary to enable reporting, manage local service delivery, inform investments and support regulation (UN-Habitat, 2023). While regulator or service delivery monitoring often focuses on finance, capacity and customer service, indicators relating to health risks should also be included and may also require improved regulatory systems that enable assessments of risks across the entire chain, rather than just monitoring compliance with treatment plant effluent standards.

7.3.4.3 Detailed empirical assessments

Detailed empirical assessments, such as those conducted in Papers 2 and 3, remain important to understand the risks associated with specific OSSs, their implementation or context. These studies often inform assumptions used in broader monitoring frameworks and are invaluable in understanding transmission pathways and localised hazards. The monitoring of risks in Paper 4 relied on several assumptions, such as sludge accumulation rates, containment size and inflows, that would benefit from national studies to develop locally specific assumptions. Studies on specific pathogen transmission pathways such as Paper 2 on septic tank effluent, studies on flies (Capone, Berendes, et al., 2021) or groundwater contamination (Paper 3) help to understand the transfer of pathogens from sanitation to exposure, although it is often difficult to scale the findings to other contexts given many aspects of pathogen release, transport, and exposure are context specific. This underscores the importance of conducting tailored empirical research with similar conditions in different regions to establish whether findings are generalisable and could provide inputs to larger-scale risk assessments and sanitation strategies. New technologies could support empirical studies, with studies already using remote sensors to detect wastewater levels in septic tanks or genome sequencing of pathogens and antimicrobial-resistant genes (Oduah & Ogunye, 2023; Tan et al., 2021).

The following section on the importance of in-situ pathogen studies is linked to empirical studies as an important method for health risk assessments, and the future research section below provides some critical research areas that would further our understanding of the function and risks of OSSs.

7.3.5 In-situ pathogen data is important but has challenges

Understanding how pathogens are removed and discharged from OSSs into the environment is crucial for assessing health risks, particularly in LICs where there is a high prevalence of pathogens in the local environment, yet limited data. Given the challenges of monitoring pathogens, as discussed further below, many studies in LICs have focused on indicator organisms such as *E. coli* when monitoring OSS discharge or environmental contamination in LICs (Manga et al., 2022; Y. Wang et al., 2022). However various authors critique that indicators are a poor substitute for understanding pathogen discharge from sanitation and could underestimate the risks (Mraz et al., 2021; M. Wang et al., 2021). *E. coli* does not necessarily represent the behaviour, reduction, and die-off of a broad range of pathogens and although a small sample, this could be seen in the lower removal of *E. coli* compared with *Giardia* in Paper 2. Furthermore, *E. coli* detection cannot differentiate between human and animal contamination sources, complicating attribution in LICs where livestock frequently interact with water supplies and household environments as was found in Paper 3; noting that there may also be other sources of human excreta in the environment beside OSSs. While the data from Paper 2 contributes new findings, there were limited studies to compare whether these findings were representative of septic tanks in other contexts. There remains a major gap in data from the context of LMICs, and given the type of sanitation, implementation conditions (including poor implementation), and nature of pathogen inflows that differ from HICs, it is often difficult to compare findings with available data or laboratory-based studies from HICs. These limitations underscore the need for more representative pathogen monitoring methods to better understand public health risks in the context of LICs.

While pathogen data is important, there are multiple challenges in collecting and analysing pathogens from OSSs in LMICs compared to wastewater monitoring, due to their highly variable inflows, small inflow populations, and the effects of storage. As noted in Paper 2, OSSs receive inflows from a much smaller population than the flows monitored in a sewer, which creates a challenge in identifying what pathogens to measure and that the inflows are specific to the level of illness of the users. Populations in LICs, particularly the slum areas analysed in Dhaka, are expected to have higher levels of pathogens than HICs but the pathogen prevalence and shedding patterns vary across locations and time, which complicates comparisons (Capone, Berendes, et al., 2021; Stenström et al., 2011). As was noted in Paper 2, sampling inflows to OSSs is hard due to difficult access to inflow pipes and challenges in obtaining a representative sample given the intermittent and user-specific nature of inflows. Further research is needed to identify whether estimates of pathogen inflows based on local health data and water use as done in Paper 2, are equivalent or more representative than can be achieved through a financially viable sampling strategy. While these estimations provided valuable insights, they could not capture real-time conditions, adding uncertainty to comparisons between inflow and effluent concentrations. For example, *Salmonella typhi* was absent in effluent samples but estimated to be present in low concentrations in inflows, raising questions about its removal or absence during the sampling period. However, this could also occur with in-situ sampling of inflows due to storage. Given the increase in pathogen surveillance of wastewater, various authors suggest OSS sludge, effluent or drainage could also be used for public health information (Capone et al., 2020; Strande, 2024), however, the storage in OSSs means that it is not real-time and the variability in OSS implementation and pathogen inflows makes sampling difficult (Delgado Vela et al., 2024).

Pathogen monitoring in LICs faces broader challenges, including resource limitations, logistical issues, and the need for advanced laboratory techniques. Given the above-mentioned variability of inflows and different prevalence of pathogens in LICs, in Paper 2 it was necessary to first screen the drain and effluent samples to identify what pathogens were present by sending the samples to the USA for analysis with TaqMan Array Cards, followed by qPCR which was available on-site and could measure the concentration of targeted pathogens (Amin et al., 2020). In many LMICs, these methods are challenging to deploy due to inadequate facilities, capacity or resources, although some local facilities such as the icddr,b research centre in Dhaka demonstrate exceptions. While monitoring pathogens is valuable due to the ability to translate pathogen concentrations to quantifiable and relatable health risks using QMRA, there are critiques of this approach for LMICs given the dose-response curves are based on relatively healthy HICs and low doses (Brouwer et al., 2018; Goddard et al., 2020) and also the challenge that units of qPCR do not translate directly to units of current dose-response curves. Despite these challenges, the study's findings highlight the significant health risks posed by high pathogen concentrations in OSS effluent and underscore the need for more comprehensive data to better understand variability, treatment performance, and environmental implications in LICs.

7.4 Limitations

This research inevitably addresses only certain aspects of the health risks associated with OSSs, with findings shaped by the specific conditions and methods used for their assessment. This section summarises the overarching limitations of this research, focusing firstly on those relating to the research scope and, secondly, on constraints related to methods. These build upon the detailed limitations outlined in the discussion sections of each paper.

From an engineering background, with experience primarily in the wetter climates of Asia, this technical and regional perspective informed the scope of risks assessed and approaches employed. While Paper 4 covered multiple countries and regions, the empirical case studies were concentrated in low-income urban regions of Asia, predominately in tropical climates with water-flush toilets. As a result, the findings are likely less applicable to vastly different contexts, such as Sub-Saharan Africa, where dry toilets are more common. Similarly, in higher-income areas, even when flush toilets are used, risks related to effluent discharge are expected to differ due to variations in discharge to the environment and human interactions with drains or shallow wells. Nevertheless, the findings are relevant to a large global population relying on water-flush OSSs in tropical climates.

Although the WHO Guidelines on Sanitation and Health (WHO, 2018) addresses risks across the entire sanitation service chain and uses a broad definition of health, this study focused on the first steps of the service chain and primarily assessed risks associated with exposure to faecal pathogens. The research concentrated on the access, containment and emptying of OSSs, excluding risks associated with sewer systems, transport and treatment. Overflows and leakages from sewer systems, as well as the discharge of inadequately treated excreta to the environment during transport and treatment, were not assessed. However, the methods could be adapted to monitor these aspects, improving the assessment of risks across the entire service chain.

Additionally, this research focused narrowly on faecal contamination, excluding other significant health risks such as privacy, safety, and well-being, as well as environmental health concerns like nutrient, chemical and heavy metal pollution (EPA Ireland, 2021; WHO, 2018).

Methodologically, the empirical studies were constrained by small sample sizes, limiting the statistical significance and generalisability of the findings. While the research prioritised in-depth assessments to understand how implementation influences risks for particular hazards and in specific contexts, the scope was insufficient to capture the full diversity of OSS risks or validate findings across other regions. Designing the study for Paper 3 posed significant challenges, particularly balancing the ideal conditions for research with in-field realities. For example, the improvement in the availability of sites with septic tanks that comply with design standards or water supplies with minimum protection. Alternative methods, such as constructing piezometers to reduce local contamination or installing septic tanks to assess containment impacts, were explored but were unfeasible due to time, budget and site constraints. The research in Paper 3 would have benefited from methods to distinguish between human and animal-origin pathogens, given the presence of livestock, which emerged as a significant risk factor. The methods used in Paper 4 relied on several assumptions and generalisations, with data presented as country averages. While this facilitated analysis and interpretation, as discussed elsewhere in the thesis, both averaging at a national scale and applying generic criteria for risk assessment inevitably oversimplified the complex realities. Further application of these methods requires a clear explanation of assumptions made to avoid misinterpretation of the intention and constraints of the findings.

Furthermore, the thesis primarily examines hazards without a detailed assessment of exposure or translating findings into quantifiable health outcomes. While the studies touched on exposure by identifying where hazards occur and, in some cases, how populations are exposed, there was limited assessment of exposure quantities and illness risks. For instance, Paper 2 estimated the probability of illness from exposure to pathogens in drains but was constrained to only assess Norovirus and Giardia as the other pathogens could not easily be translated from the genome units calculated with PCR to units in CFU used in dose-response models. These calculations were also generalised relying on assumptions from literature rather than measured data. Additional exposure assessments could improve understanding of human interaction with faecal contamination in the environment. Tools such as QMRA offer potential for quantifying risks, though these are also limited by the assumptions involved and their applicability to populations in LMICs and pathways with high concentrations of multiple pathogens. Focusing solely on pathogens and *E. coli* excludes other harmful environmental releases, such as antimicrobial resistance. Translating hazards into quantified health outcomes could improve the uptake of findings by policymakers, though the broader argument remains that reducing the release of excreta to the environment is critical.

These limitations are also one challenge of conducting research at the intersect of engineering and public health, which are both wide and complex fields and methods are limited to only include certain aspects of each approach. Despite these limitations, these findings have important implications for research, policy and practice.

7.5 Implications for research, policy and practice

7.5.1 Contribution to knowledge

This thesis makes four main novel contributions to knowledge and literature on sanitation and health, focused on OSSs in LMICs. These contributions are:

Integration of public health and engineering perspectives in health risk assessment. This research presents an evidence base that confirms health risks remain a persistent issue for sanitation services in LMICs. It emphasises the ongoing relevance of the public health engineering approach that has waned in recent years with competing environmental, financial and entrepreneurship drivers. By taking a multidisciplinary approach to monitor and assess health risks from sanitation, the methods considered not only the access to sanitation facilities but, importantly, their implementation, discharge of pathogens, and pathways of faecal transmission. The numerous implementation issues further underscore the importance of considering engineering aspects in health risk assessments, noting that improved or even ‘safely managed’ sanitation facilities may still discharge pathogens into the environment over their lifespan, thereby limiting positive health outcomes. This integrated approach underscores the significance of evaluating the health risks of sanitation within the broader context of how they interact with the environment and how they are designed, built and operated in practice.

Novel data on pathogen discharge from septic tanks to drains. This study provides original quantitative data on pathogen discharges from septic tank effluent and their concentrations in drainage systems, contributing to the sparse data on pathogen discharges from OSS. Detailed analysis highlights the interaction between sanitation infrastructure and the environment, illustrating the health implications of design and implementation practices. While sanitation systems are not intended to discharge directly to the environment, this research provides evidence that this is a common issue in many contexts, such as the Asian countries included in this research. These findings emphasise the importance of research focusing on how systems are actually used rather than their ideal design and operating conditions. While the limited reduction of pathogens in septic tanks may not surprise many academics, quantifying the extent of this hazard brings greater attention to the risk and awareness of the need for improved effluent management, particularly where subsurface infiltration is difficult.

Development of monitoring approaches to assess diverse health risks and contamination pathways associated with OSSs. This thesis presents a range of monitoring and assessment approaches tailored to different scales of data use. It identifies gaps in global sanitation monitoring approaches and proposes indicators that are tested and ready for immediate integration into national and sub-national systems. Furthermore, it offers quantitative evidence of health risks across diverse contexts of LMICs, showcasing variability in risks while underscoring the significant health impacts of sanitation systems classified as 'safely managed'. The empirical study methods included engineering considerations in environmental quality monitoring studies, which enabled assessment of the diverse pathways that sanitation systems transmit pathogens to the environment and to humans. The studies addressed limitations identified in previous research through analysis of pathogens rather than *E. coli* discharge from septic tanks and through the mixed methods approach and statistical analysis of groundwater contamination. In Paper 3, the new methods included conducting a census approach to overcome issues of population density and varied environmental and geophysical properties, infrastructure inspections, spatial mapping, groundwater depth measurements, and repeat water quality analyses. These methods present expanded ways to assess sanitation contamination pathways, including comprehensive assessments of horizontal and vertical separation, density, and consideration of multiple variables.

Critique of generalised terminology and conceptual gaps in OSS monitoring. The thesis identified limitations in generalised terminology used for monitoring OSSs as well as gaps in discourse on effluent management. The sector's focus on management of faecal sludge often neglects the equally important management of the liquid effluent stream, which is often absent from discussions and diagrams of the OSS service chain (see Figure 7.2). The importance of identifying critical physical features of OSS infrastructure, how they are implemented and the physical context in which they are used are important. Generalised terms such as OSS, septic tank or pit latrine refer to diverse systems with varied risks. The research emphasises the need for future studies to clearly define the features of OSSs, their implementation, and the environmental settings to better understand how the results may apply to other contexts.

In summary, this thesis contributes a multidimensional perspective to sanitation research, emphasising health risks, implementation practices, and monitoring challenges in LMICs. As discussed below, the findings have immediate implications for policy and practice, while also setting a foundation for future research to improve global sanitation outcomes.

7.5.2 Implications for policy and practice

This thesis provides various contributions to sanitation practice and policy, emphasising the importance of considering public health in sanitation investments and system design in LMICs. The key contributions are outlined below:

Reintegration of public health into sanitation prioritisation. This research underscores the critical role of public health in sanitation policy, arguing that addressing health risks should be reinstated as a central objective for sanitation investments, particularly in LMICs. The recognition of the health benefits drove historical progress in sanitation and while I recognise the importance of environmental protection, circular economy, and climate considerations, these should complement, not replace, public health priorities. This research aims to provide evidence that can further increase attention to the health risks associated with sanitation; while emphasising that engineering and planning decisions need to assess and address these risks in planning, design and management. Agreeing with Cummings et al. (2024), with increasing threats of climate change, disease pandemics and resource shortages, cross-disciplinary collaboration and integrated approaches are needed where public health principles guide engineering solutions to achieve resilient and adaptable sanitation systems.

Beyond binary definitions of sanitation access and safety to reduce public health risks. This research challenges the simplistic notion of access versus no access to sanitation, highlighting the necessity of understanding how systems are implemented and function within specific contexts. It reveals that even sanitation systems classified as 'safe' may discharge significant pathogens into the environment through a wide variety of pathways, presenting ongoing risks to public health. There needs to be greater emphasis on evaluating sanitation infrastructure based on performance and contextual suitability rather than generalised classifications. This includes promoting monitoring definitions and designs that are explicit in the features and implementation factors that contribute to reducing risks, rather than assuming universal understanding by all sanitation stakeholders of what terms mean or how systems should function. These features and the complementary indicators should be considered in the targets and approaches to monitor sanitation in the post-SDG era.

Context-specific sanitation investments. Sanitation investments should be made with consideration of public health risks that are likely specific to the local context. This requires evidence to understand the nature of risk in different locations. Global, national, local and empirical studies can provide different specificity of evidence for different types of decisions. This study demonstrated that there is no universal health-focused sanitation solution for all contexts and the priority area and type of solution may differ significantly across locations. Below is a somewhat detailed set of examples that demonstrate the importance of weighing up risks and considering the local context in improvement options.

- Decisions on where to prioritise sewerage investments should not only focus on serving the densest areas or those already customers of piped water services but also consider the priority areas where sewerage could contribute to the greatest health risk reductions. For example, areas where OSSs are not functioning or pose health risks due to low infiltration soils, shallow groundwater or the use of shallow wells for drinking could benefit from sewered sanitation. Implementation of OSSs in areas with poor soil permeability presents a high likelihood that they will be connected to drains and cost comparisons with sewerage should include a complete OSS solution with effluent management.
- In areas where the soil is suitable for infiltration, ensuring effluent discharges to the soil rather than the surface should be a priority, although the risk to drinking water should be considered. In dense or low-income areas, smaller tanks may provide budget and space to construct subsurface infiltration systems, which should be promoted as part of any septic tank solution and not an optional

extra. This is important for traditional septic tanks as well as prefabricated PVC systems, China's three-chamber septic tanks, ABRs, or decentralised treatment, all of which require further effluent management due to health risks.

- OSSs and wells will continue to be used in dense areas, shallow groundwater areas or poor-quality soils and may require context-specific risk management beyond setback distances. Although not investigated, options to reduce risk of OSS contaminating groundwater could also include i) increasing the vertical distance to groundwater (e.g. twin pits rather than single deep pits, or horizontal leach fields rather than soak pits), ii) slow infiltration through linings (e.g. geofabric or sand barriers), or iii) reduce hydraulic load (e.g. low-flush toilets or blackwater-only systems). Investments in OSS improvements to reduce groundwater contamination risk should also consider the role and options to reduce risk through water infrastructure or other local pathways.
- Regular emptying services could prioritise implementation in areas of greatest health risk, such as where OSSs are nearing their timely threshold, OSSs with outlets to drains, or areas where overflow would have a greater impact. The frequency of emptying and obligating emptying must also weigh up the health benefits of emptying, the financial and operational burden to the household, and the risks of unsafe emptying, transport and disposal.

These approaches advocate for understanding site-specific risks and designing sanitation systems that address those risks rather than pursuing uniform solutions driven solely by economic objectives or business as usual. While comparing against standards and ideal implementation, it is essential to recognise that millions of poorly implemented systems exist, and investments should not only focus on new systems but also on reducing risks for existing systems through modifications or management. More attention is needed on how to reduce the risks of existing sanitation systems and what level of risks are acceptable in the short- and long-term given improvements may be incremental. This also requires assessing whether sanitation is the priority investment to reduce risks compared with other infrastructure or behaviour interventions.

Integration of water, sanitation, and drainage systems. This research highlights the interconnected risks of water, sanitation, and drainage systems, particularly in dense urban environments. Sanitation cannot be assessed in isolation, as poorly managed drainage systems can exacerbate flooding, impair OSS functionality, and wash pathogens into surface environments. Similarly, increasing water use can lead to larger volumes of contaminated wastewater, stressing existing sanitation systems, while untreated discharge from OSSs can contaminate surface and groundwater supplies. While this thesis focuses on blackwater, greywater must also be managed, and in LMICs greywater is often not discharged to OSSs. Not connecting greywater may be beneficial to OSS function, such as increasing the hydraulic retention time or reduced hydraulic loading into soils. However, greywater may also pose health risks that need to be managed. The use, contamination and discharge of greywater are likely to be context specific and future studies on OSSs and sanitation in LMICs would benefit from clarifying how greywater is managed. The integration of water, sanitation and drainage risk assessment and planning will be increasingly important with climate change. Increased flooding, droughts and extreme events are expected to exacerbate the interconnected risks of public health, water systems and the built environment, requiring adaptive and cross-disciplinary strategies.

Improved OSS standards, regulation and enforcement. This thesis identifies critical gaps in OSS standards and enforcement in LICs where existing standards and norms may not always suit conditions or are poorly applied. Even where regulation exist, they are not always well suited to the types of systems used and the local conditions in which they are built. Effective design, construction and operation require clear standards and norms, including for effluent management and approaches to assess and mitigate risks. These should provide options that can be tailored to suit the different inflows (e.g. sizing to include or exclude greywater), different geohydrological conditions, and use in high-density urban settings. Rather than relying on generic siting or design standards from HICs, innovative, context-specific solutions are needed. Although it relates to sewerage, innovations in design and adjusting standards to suit local conditions led to the approval and scale up of condominial sewers in Brazil. Better communication of standards and guidelines is also needed to the range of stakeholders involved in OSS implementation (i.e. practitioners, including masons, planners, and households). Clear, contextually relevant design materials, coupled with training on adapting systems to suit local conditions, could improve implementation. Regulatory frameworks must go beyond construction oversight to address ongoing health risks, such as enforcing effluent management, mandating emptying where necessary, or regulating appropriate sizing and operation. Countries like France and Ireland demonstrate that OSS can be effectively regulated to reduce health risks beyond construction, through routine inspections to ensure ongoing safe operation.

Data driven risk assessment and monitoring. The thesis emphasises the need for risk assessments tailored to different scales. While global assessments rely on generalisations and are helpful for an overarching assessment of progress and gaps, site-specific data is critical for designing effective solutions. While health risk assessments are often qualitative, these may limit the nuanced comparison between different solutions or weigh up which pathways are the greatest hazard. Quantitative data is therefore valuable to improve decision-making and prioritisation and inform which solutions can contribute to the progressive reduction of risks. Quantifying hazards can enable health aspects to be used in decision-making, such as benefit–cost comparisons between options, as well as tracking progress over time. As noted in the CWIS framework and WHO and UNICEF's steps to achieve safely managed sanitation, data and monitoring are critical to sustainable services, while data and feedback are also core to climate adaptation and resilience (Schrecongost et al., 2020; WHO & UNICEF, 2024; Willetts et al., 2022). While it would be easiest to communicate health risks in outcomes, such as rates of illness or DALYs, these often require many assumptions that are often based on research from HICs. It is important for both the approaches taken in this paper and any studies that do calculate health outcomes, to be clear on any underlying generalisations or assumptions to avoid misinterpretation and ensure appropriate use of the findings.

7.5.3 Future research agenda

Below are several areas for future research. The first section proposes research that extends from the methods and scope applied in this thesis, while the second section covers a broader scope to address outstanding knowledge and technical gaps and research that could support the translation of these ideas to practice.

The following research focuses on extending from the methods used in this thesis to apply in different contexts and scales.

- **Applying methods across diverse contexts:** Extending the application of complementary indicators to varied urban and rural settings in Africa, the Americas, and other LMICs would help assess their broader relevance and adaptability. This would be valuable to assess global applicability and feasibility to include some indicators in global monitoring beyond 2030. Further research could refine these indicators, incorporating new data on local factors or improve assumptions used in indicator analysis. Specific data includes national sludge accumulation rates and containment sizes, refined calculations of timely emptying thresholds from research on optimal filling volumes, or alternative measures to assess OHS risks. Empirical studies could also improve understanding of the potential health impact of each indicator to inform the prioritisation when multiple risks are present.

- **Expanding complementary indicators for health risks in other contexts:** Additional complementary indicators may be required to assess sanitation risks in contexts beyond those considered in this research. For example, for dry toilets, sewerage systems, and wastewater and sludge conveyance, treatment, and disposal in LMICs. Service indicators cannot be assessed through household surveys and would need to be integrated into administrative or service provider data collection systems.
- **Scaling and expanding empirical studies:** Both empirical studies in this thesis were constrained by sample size due to budget and site limitations. Larger-scale studies could enhance explanatory power, particularly in groundwater research, where multiple contamination pathways introduce significant variability. For Paper 2, expanded sampling could address pathogen shedding variability among users and explore different geographic settings to capture location-specific pathogen profiles. Moreover, analysing a larger number of septic tanks with varying sludge depths and emptying frequencies could confirm whether regular emptying effectively reduces pathogen discharge.

The following studies could address outstanding gaps in understanding pathogen removal and transmission related to OSSs. While some have been previously recommended, I have included them here as ongoing gaps that extend from this thesis or help translate the findings to practice

- **Pathogen dynamics in septic tanks:** Questions remain about the mechanisms of pathogen removal within septic tanks, including the division of pathogens between sludge and supernatant and the effects of design and operational features on pathogen reduction. Studies could examine how pathogens die-off, settle, or are otherwise removed and the influence of implementation on this. Manga et al. (2022) and Musaazi et al. (2023) also emphasised the need for improved analyses of these processes.
- **Improved source identification in the assessment of environmental contamination:** While the methods in Paper 3 controlled for many variables affecting contamination pathways in groundwater, limitations remain. While *E. coli* is a feasible method to detect contamination, it cannot differentiate between human and animal contamination. Future research should consider whether more advanced water quality analysis techniques that could enable the identification of human-specific contamination markers are feasible for LMIC settings. This is important in many areas in LICs with significant livestock populations and has been tested with mixed success in other studies (Mertens et al., 2023; Odagiri et al.,

2016). The importance of managing both animal and human contamination is growing in attention with the One Health approach (Yasobnat et al., 2022).

- **Groundwater risk reduction and monitoring:** Effective strategies for groundwater risk management beyond siting guidelines require validation and refinement. Future studies could develop matrix-based approaches incorporating unsaturated soil depth, OSS types and hydraulic loading alongside minimum required well safety features. Emerging technologies such as satellite data could help to identify groundwater depth and soil type, as these data are commonly unavailability in LMICs. Dedicated monitoring wells, rather than household wells, could improve the isolation of OSSs and aquifer contamination pathways by limiting contamination from well infrastructure and use. Although there are logistical challenges to implementing this in practice. Options to reduce risks of existing systems are also needed, such as geofabric linings, reduced inflows, whether sludge removal increases or decreases contamination risks, or alternative effluent management solutions such as shallow or mounded infiltration fields in high-water-table areas.
- **Optimising OSS sizing, emptying and greywater management:** Further research is needed to clarify the health risks associated with greywater discharge, including the different management approaches in LMICs and levels of faecal contamination. The benefits and disadvantages of integrating greywater into OSSs should be explored, considering septic tank function, effluent management and hydraulic loading for groundwater risks. OSS sizing and emptying frequency should also be analysed to optimise for improving health outcomes. This could include developing approaches to compare the risks of delaying emptying versus those associated with unsafe emptying and disposal practices. It must also be recognised that even if leaving in-situ is currently the safest solution, all OSSs will ultimately fill, and developing safe emptying services are necessary for long-term risk reduction.
- **Innovative solutions for high-risk areas:** While this thesis presents many challenges for safely managing OSSs in the context of LMICs, there remain many gaps in solutions to address these issues. Research should focus on developing effluent management strategies for areas not suitable for subsurface infiltration and without short-term plans for sewerage (i.e. Dhaka slum areas). This will likely require innovations for sewers in dense areas as well as innovations to address the millions of poorly implemented OSSs currently in use. This could include mechanisms to add subsurface infiltration systems where feasible, investigate effluent filter options, management improvements such as regular emptying or reducing water use, or reducing exposure such as by covering open drains. A model of pathogen flows in Dhaka, conducted under the same project as Paper 2,

demonstrates an approach to compare potential health risk reductions for different sanitation improvements (Foster, Falletta, et al., 2021).

- **Quantifying health risks for decision-making:** While the thesis predominately focused on pathogen discharges rather than health outcomes, QMRA can enable quantification and comparisons of health risks in measures that can be understood by policy, decision-makers and the public. Future studies could further address gaps, optimise the approach and assumptions in application of QMRA to the context of LMICs for assessing water, sanitation and environmental risks (Amatobi & Agunwamba, 2022). In parallel, further discussion between engineering and health sector experts could determine whether reducing the discharge of pathogens to the environment is an adequate target for sanitation investments, given the potential limitations and generalisations of QMRA. There is also a need to discuss acceptable levels of risk and progressive risk reduction, given addressing sanitation improvements will require prioritisation between risks and gradual improvements over time.
- **Integrating public health with broader sanitation drivers:** While this thesis underscores prioritising public health in sanitation policy, further research should explore how to balance health outcomes with other critical factors, such as financial constraints, institutional capacity, user preferences, and behavioural considerations. An interdisciplinary approach is essential for designing sustainable, scalable, and user-centric sanitation solutions.

This research agenda builds on the foundation of this thesis and aims to address the critical gaps and challenges in sanitation research and practice. Future research in these areas will improve our understanding of OSSs as they are implemented in the context of LMICs and can contribute to more resilient, health-focused, and contextually appropriate sanitation systems.

8. Conclusion

OSSs serve over 3.6 billion people globally and their use is increasing faster than sewer connections in both urban and rural areas. However, the health risks associated with OSSs remain a major concern, particularly in LMICs, where a high burden of faecal-related diseases persists. In HICs, improved sanitation services and reduced public health risks have shifted sanitation investments priorities from health to environmental and economic drivers. In contrast, LMICs continue to face severe public health challenges. This thesis argues for a renewed focus on public health as a driver for sanitation investments in LMICs, yet the literature review revealed that this is limited by a lack of data on OSS related health risks. By examining the extent OSSs are implemented and monitored to reduce public health risks, this research provides new evidence and methods to inform more effective sanitation investments that prioritise public health outcomes.

Addressing the first research question on the extent OSSs are implemented in ways that reduce public health risks, I conducted two empirical studies and analysed household survey data applying an integrated engineering and public health approach, focusing on septic tank systems and cesspools in Asia. These studies demonstrated that OSS implementation often does not comply with design standards or guidelines, although the health implications vary. Effluent discharge to drains presents a significant risk to public health, whereas the relationship between faecal contamination in wells and lateral separation from OSSs was inconclusive, however shallow groundwater depths showed increased contamination risk.

In response to the second research question on how monitoring data can better reflect health risks, I examined various scales of monitoring and assessment, as the specificity of data needed for different decisions and audiences varies. The assessment of complementary indicators found that global monitoring substantially underestimates OSS health risks, demonstrating the need to target a service level beyond the current definition of 'safely managed' if health objectives are to be achieved. The variability of risks highlighted the critical need for local data to inform decisions, and the proposed monitoring improvements could be integrated into local or national monitoring frameworks or inform post-SDG targets. While the empirical studies provide valuable insights into the relationship between OSS implementation and faecal pathogen transmission, challenges persist in monitoring pathogens in LMICs and in generalising findings across diverse systems and contexts. Applying these methods in varied contexts could improve understanding of the broader application of findings and contribute to refining assumptions used in global or national monitoring to more accurately reflect local variabilities and risks.

This research uses novel methods to contribute new evidence on the multiple risks associated with OSSs and the pathogen discharge from septic tanks in a low-income urban area. It introduces interdisciplinary methods that integrate public health and engineering perspectives to assess health risks at multiple scales and reflects on how these assessments could inform improvements to better protect public health. Complementary indicators offer a systematic yet adaptable approach to assess toilet, containment and emptying risks, which can be integrated into local or national monitoring. This approach could be extended to develop complementary indicators to assess risks during transport and treatment. Looking ahead, this research highlights the need for research and monitoring to more clearly define key features of the OSSs, as generalised terms hinder interpretation and comparability of results. In addition, the thesis proposes improved visual communication to raise awareness of the importance of effluent management, building from recent discussions on clarifying terminology used for faecal sludge and non-sewer sanitation.

The evidence and published articles justify an increase awareness of the critical importance of prioritising health, while the variability of issues demonstrates that there is no universal solution to address OSS risks. Instead, local assessment and prioritisation of risks are essential, requiring major improvements to national and sub-national monitoring systems. Implementation strategies must be adapted to suit local conditions, potentially requiring alternative designs or standards compared to those used in HICs. In many urban locations, there is an urgent need to improve effluent management, such as enforcing the use of subsurface infiltration systems where feasible or implementing alternative effluent management systems. However, there are limited alternative solutions, highlighting the need for further research and innovation to develop technical and operational options that mitigate risks, particularly for OSSs in areas with poor soil permeability or shallow groundwater.

Increased awareness of the importance of prioritising risks, along with enhanced public health training is needed for development partners, engineers, service providers and masons. This capacity building would enable better adaptation of planning, design or operation to suit local conditions and risks, which are also important skills for adapting to climate hazards. The empirical methods used in this study could be applied in other contexts to generate broader evidence on implementation and risks in varied contexts and to refine assumptions used in the complementary indicators. Ultimately, addressing these risks requires more than data and monitoring, such as improved standards and regulation, policies integrating sanitation and health, and related planning, finance and behaviour change initiatives that warrant future research and action.

While risks of OSSs may be known by academics, this awareness has not effectively translated into practice. Decision-makers must move beyond viewing OSSs as a universally viable solution in areas without sewer systems. Instead, they need to critically assess risks, identifying the most effective solutions that ensure sanitation investments genuinely reduce public health burdens by minimising environmental contamination and human exposure to pathogens. The promotion of OSSs, particularly in dense urban settings, often overlooks their suitability for context, not just missing potential benefits but potentially increasing health risks. Effluent management is a relatively unexplored aspect of OSSs and will require innovative approaches to adapt the millions of existing systems that continue to pose public health risks. Effective solutions must integrate technical and operational improvements with exposure management, alongside broader considerations of water supply and drainage. This thesis aspires to stimulate improved collection and use of data on OSS risks to guide more informed and context-specific sanitation investments that protect public health.

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Appendices

A. Paper 2 supplementary materials

B. Paper 3 supplementary materials

C. Paper 4 supplementary materials

Appendix A – Paper 2 supplementary materials

Appendix A – Paper 2 Supplementary Information

Unsafe containment: Public health risks of septic tanks discharging to drains in Dhaka Bangladesh

Study area

Table S1. Details of study site and results on sanitation use

General study area			
Total compounds	172	Mean households per compound (SD)	8.5 (4.8)
Total households	1493	Mean people per households (SD)	3.2 (1.1)
Total residents	4792	% government compounds	80%
		% private compounds	20%
Sanitation		**Water supply**	
% private toilet	7%	% piped to household	9%
% share sanitation with others	93%	% piped to compound	91%
Sanitation use	n=173		Mean (SD)
Septic tank (two chamber)	24%	Toilet facilities per compound	1.4 (1.1)
Holding tank (single chamber)	3%	Toilet pans per facility	2.4 (2.0)
Ring and slab tank/pit	2%	Households per toilet facility (all respondents)	6.9 (3.7)
Tank/pit (unsure type)	1%	Households per toilet facility (using septic tanks)	8.9 (3.6)
Direct to drain (observed)	49%	Users per toilet facility (all respondents)	21.1 (11.2)
Direct to drain (reported)	20%	Users per toilet facility (using septic tanks)	24.9 (9.8)
Hanging toilet	1%	Households per toilet pan	4.0
Don't know	1%	Users per toilet pan	12.2

Water use

Table S2. Calculated water use based on meter readings and water bills

Unit	Sample	Average	Median	Range	SD	IQR
Water use per person L/ day	Compounds with septic tanks (n=24)	208	196	63-494	106	130-249
	All compounds (n=97)	189	146	14-794	127	115-226
Proportion water use	Toilet flushing	6%	Blackwater discharged to toilet/septic tank			
	Cleaning	5%	Greywater discharged to open drain			
	Dishes	5%				
	Clothes	20%				
	Floors	2%				
	Bathing/showering	54%				
	Cooking	5%				
	Drinking	3%	Assumed not discharged			
Estimated blackwater inflow to septic tanks L/p/d	Median	11.8	6% flushing x median water use compounds with septic tanks			
	Low (IQ1)	7.8	6% flushing x IQ1 water use compounds with septic tanks			
	High (IQ3)	15.0	6% flushing x IQ3 water use compounds with septic tanks			

Unit	Sample	Average	Median	Range	SD	IQR
Estimated greywater flow L/p/d	Median	190	Assumed 97% water used discharged to greywater (from data and literature) x 196L/p/d median water use in compounds with septic tanks.			

Note that these per capita water use may appear high but align with high values reported previously for Dhaka which has ranged from averages of 139 to 310 L/person/day.[1,2]

Sludge accumulation and function

The sludge depth in both chambers of the tanks was measured with a commercially available septic checker, which is a long clear tube that captures a vertical profile of the septic tank layers (sludge, supernatant, scum) that were then measured. Seven tanks from different streets were sampled to cover the range of operating durations and depths (Table S3). The volume of six tanks with both sludge depth measurements was calculated using the tank area from the design drawings and this volume then used to calculate sludge accumulation rates considering the census data on users and years of operation. One sampled tank was excluded as only one chamber could be measured. The average sludge accumulation rate (28.8L/p/year) aligned with the only other published study from Bangladesh (30-50L/p/year in rural areas)[3] and global average findings for water-flushed septic tanks (20-70L/p/yr).[4–6] This data was used to estimate sludge depth in the remaining tanks, considering the number of users, age and the total tank volume from design drawings. Based on the calculated sludge volume and water use (median per person use 196*6% L/p/d and users), the hydraulic retention time was calculated. Tanks with sludge volumes lower than 66% of tank capacity and hydraulic retention times of more than 24 hours were considered functioning per design standards (Table S4).

Table S3. Summary data of septic tank depth assessment using sludge checker

	Years operating	Users	Height sludge % total measured tank depth		Sludge volume (m3)	Sludge accumulation (L/p/year)
			1st chamber	2nd chamber		
n	7	7	6	7	6	6
Average	3.0	31.1	44%	39%	2.3	28.8
SD	1.5	6.2	26%	28%	1.1	12.2

Table S4. Septic tank function assessment

Drain	Total septic tanks	Not functioning	Functioning	% population using ST	% population using functioning ST
A – north	15	8	7	90%	30%
A – south	11	5	6	64%	25%
B combined	4		4	13%	13%
C – north	1		1	7%	7%
C- south	0		0	0%	0%
D combined	9		9	15%	15%
Grand Total	**40**	**13**	**27**	**24%**	**14%**

Septic tank duplicates

Repeat samples collected two months apart for four tanks are presented in Table S5. For the four samples and five pathogens assessed (20 data pairs), nine pairs were negative for pathogens in both samples, five pairs were positive in only one sample, and ten pairs were positive in both samples. The average relative difference is calculated for these positive pairs (see Table S5). The difference in concentration between repeat measures from the same tank varied from 0.05 log_{10} GC/100mL for Norovirus GII to 2.98 log_{10} MPN/100mL for *E. coli*.

Table S5. Duplicate septic tank effluent sample pathogen and E. coli concentration and difference

Pathogen concentration *log_{10} GC/100mL*	Street B Tank1		Street B Tank2		Street D Tank1		Street D Tank2		Average relative difference positive repeats	Average log difference positive repeats
Season	Dry	Dry	Dry	Wet	Dry	Dry	Wet	Wet		
Norovirus (GII)	4.2	4.2	5.3	0.0	5.6	4.3	0	0	13%	0.6
V. cholerae	0	0	0	0	0	3.1	3.6	0.0		
***S.* Typhi**	0	0	0	0	0	0	0	0		
Giardia	0	0	2.5	0	0	3.0	0	0		
Shigella	3.5	2.8	3.5	2.9	4.1	2.0	1.1	3.3	53%	1.4
***E. coli** (log_{10} MPN/100mL)*	6.6	6.4	6.3	6.7	7.0	6.5	5.4	8.4	16%	1.1
Average									27%	1.0

Septic tank estimated influent concentration

Septic tank influent concentration was calculated for mean, low and high scenarios of prevalence, shedding and water use. The pathogen load was estimated based on the assumptions used in the pathogen flow model and sensitivity analysis detailed in the supplementary material Table S5 of Foster et al 2021.[7] The influent load was based on the available data on pathogen prevalence in the population (Table S6), the shedding load (Table S7), the weight of faeces per day from literature (243g).[8] The influent concentration was calculated using the estimated flushing volume from census data (Table S2 and S8). The influent concentration was only estimated for Norovirus GII, *Giardia* and *E. coli* as these pathogens and indicator could be compared to the measured effluent concentrations.

Table S6. Ranges for sensitivity analysis (from Foster et al. 2021, Table S5)

Pathogen	Multipliers for prevalence		Shedding	
	Low	**High**	**Low (SD)**	**High (SD)**
Norovirus (GII)	0.8 [9]	1.2 [9]	6.5 (0.5)	8.5 (1)
Giardia	0.6	1.4	4.5 (0.5)	6.5 (0.5)
E. coli	-	-	7 (0.5)	9 (0.5)

Table S7. Prevalence of pathogen shedding used for base case (from Foster et al. 2021, Table S2)

Pathogen	% of total population who are shedding		Shedding load: Mean (SD) Log_{10} organisms per gram of faeces	Burden of disease in Dhaka	Duration of shedding (days)	Duration of symptoms (days)	Asymptomatic cases
Norovirus (GII)	Symptomatic Asymptomatic	0.82% 0.67%	7.5 (0.5)[10–12]	15.7% of patients with	7 [13,14]	4 [15]	0.55 [11,16]

	Total shedders	1.49%		diarrhoea infected with norovirus[9]			
Giardia	Symptomatic Asymptomatic Total shedders	1.9% 2.1% 4.0%	5.5 (0.5) [17]	4% of people infected with *Giardia* [18–20]	n/a	11 [21]	Burden of disease estimate includes both symptomatic and asymptomatic cases
E. coli	Symptomatic Asymptomatic Total shedders	0.00% 100% 100%	8 (0.5) [22,23]				

Table S8. Arithmetic mean inflow estimate based on excreta generated, pathogen prevalence and shedding loads and water used in toilet

	Load excreted per person per day		Estimated pathogen concentration in influent				Literature [d]
			Blackwater flows [b]			Combined wastewater [c]	
	Mean	Units	Mean	Median	Range	Mean	Range
Norovirus (GII)	1.15×10^8	log_{10} GC /100mL	6.7	6.1	5.3-7.2	5.5	4-8[24]
Giardia [a]	4.92×10^7		6.4	5.7	4.3-6.9	5.2	2-5[25]
E. coli	2.43×10^9	log_{10} MPN /100mL	8.9	8.4	7.2-9.5	7.7	4-7[26,27]

Notes: a) Giardia load in genome copies, assuming 16 genome copies per cyst.[28]
b) Estimated influent concentration based on low, median and high blackwater flow volumes. Assumed 6% of water used is discharged to the toilet based on the household survey. Water inflows from census data were IQ1: 130 L/c/d, Median: 196 L/c/d, and IQ3 249 L/c/d therefore influent blackwater flows were 8 L/p/d low flows, 12 L/p/d median flows and 15 L/p/d high flows.
c) Estimated influent concentration assuming the same load within combined greywater and blackwater flows. Combined wastewater discharge is 97% daily flow (from household survey). The resultant combined wastewater flows were 126 L/p/d low flow, 190L/p/d median flow and 242L/p/d high flow.
d) Wastewater concentrations from literature converted to log_{10} GC/100mL for Norovirus GII and *Giardia* and as reported in MPN/100mL for *E.coli*

Septic tank effluent concentration results

Table S9. Comparison of effluent samples for functioning and non-functioning septic tanks

	Pathogen occurrence		Arithmetic mean concentration of positive samples			
	Functions within standards	Not functioning	Units	Functions within standards	Not functioning	Difference
FIB (*E. coli*)	100%	100%	log_{10} MPN/100mL	7.34	7.84	0.50
Norovirus GII	60%	71%	Log_{10} GC/100mL	4.60	5.25	0.65
V. *Cholerae*	40%	71%		4.26	4.29	0.03
Giardia	20%	14%		3.93	4.41	0.48
Shigella	100%	86%		3.08	6.01	2.93
Average across pathogens	64%	69%		4.64	5.56	0.92

Table S10. Summary statistics for parameters used in bivariate analysis considering only the sampled septic tanks (n=17)

Parameter	Mean	SD	Min	Max
Years Operating	3.36	1.48	1.29	4.88
Users per tank	30.61	7.88	17	52
User x Years	102.95	53.34	28.39	185.1
Sludge depth percentage	50%	31%	5%	100%
HRT (days)	10.74	13.78	0	61.26
Operation beyond design standards	41% unsafe			
Wet season (=1)	47% wet season			

Table S11. Bivariate analysis of ST effluent samples and data on use and function for sampled septic tanks (log concentration of positive samples only)

Pathogen (Positive samples)	**Norovirus GII** (11)		***Cholera*** (9)		***Giardia*** (3)		***Shigella*** (16)		***E. coli*** (17)	
Parameter	r	Sig	r	Sig	r	Sig	r	Sig	r	Sig
Years Operating	0.58	0.06	-0.12	0.76	0.07	0.95	0.48	0.06	0.18	0.48
Users per tank	0.05	0.89	0.52	0.15	1.00*	<0.01	0.36	0.17	0.15	0.57
User x Years	0.55	0.08	0.19	0.62	0.58	0.61	0.64*	0.01	0.18	0.48
Sludge depth percentage	0.55	0.08	0.19	0.63	0.58	0.61	0.64*	0.01	0.18	0.49
HRT (days)	-0.39	0.24	-0.22	0.56	-0.93	0.24	-0.65*	0.01	-0.27	0.3
Operation beyond design standards	-0.5	0.12	0.17	0.66	-0.61	0.59	-0.65*	0.01	-0.34	0.18
Wet season (=1)	0.29	0.39	-0.33	0.39	0.39	0.75	-0.04	0.89	0.52*	0.03

* Significant (2-tailed) <0.05

Table S12. Comparison of effluent from emptied tank with unemptied tanks of similar age

		Emptied tank[a] Effluent concentration	**Unemptied tanks built at same time (n=6)[b]**		**Difference: Mean Unemptied tanks – Emptied tank**
			Occurrence	**Mean effluent concentration (Range)[c]**	
Norovirus GII	GC/ 100mL	3.2	83%	5.2 (4.07,5.81)	2
V. cholerae		0	67%	4.4 (2.25,4.88)	NA[d]
S. Typhi		0	0	0	0
Giardia		0	17%	4.4	NA[d]
Shigella		2.7	83%	6.1 (2.04,6.77)	3.3
E. coli	MPN/ 100mL	6.5	100%	7.8 (5.91,8.38)	1.3

Note a) The emptied tank had an age of 4.63 years and 35 users, making for 162 user.years
b) Comparison with six unemptied tanks with similar user.years, ranging from 146-185 (average 161).
c) Arithmetic mean concentration of positive effluent samples from 6 tanks.

d) Given V. *cholerae* or *Giardia* were not detected in the effluent sample of the emptied tank, these differences were not shown.

Septic tank effluent and drain comparison

Table S13. Pathogen concentrations in septic tank influent, effluent and drains, indicating the blackwater only and the equivalent combined flows to enable comparison with combined flows in drain and in literature

		Arithmetic mean influent		Septic tank effluent		Measured drain concentration (Grab samples)			
		Black water	Equivalent wastewater[a]	Measured (blackwater only)	Equivalent wastewater (blackwater + greywater)[a]	Presence (n=30)	Mean[b]	Median	IQR[c]
Norovirus GII	Genome copies / 100mL	6.7	5.5	5.0	3.8	67%	5.04	4.20	2.50
V. cholerae				4.3	3.1	100%	5.79	5.11	1.79
S. Typhi				NA	NA	27%	3.05	2.34	0.94
Giardia		5.2	3.9	4.2	2.9	50%	4.26	4.09	0.40
Shigella				5.6	4.3	100%	5.60	4.91	1.22
E.coli	MPN/ 100mL	8.9	7.7	7.6	6.4	100%	7.66	7.17	1.03

Notes:
a. Blackwater are the flows from toilets and septic tanks. Greywater are other discharges including kitchen, washing, cleaning. Equivalent wastewater flows are the blackwater measured concentration combined with the estimated greywater flows from survey data.
b. Concentrations are the arithmetic mean of positive samples.
c. IQR is the interquartile range.

Quantitative microbial risk assessment (QMRA) to assess the probability of illness of children exposed to effluent or drain water

The probability of illness was calculated assuming children under five years old were exposed to drains a median of 14 times per year (from surveys presented by Foster et al. 2021 in Figure S3) with an assumed 1mL ingestion per drain exposure, as assumed in the Sanipath tool.[29] The pathogen concentration in drains excluded non-detects; therefore, to account for some samples being absent for pathogens, the exposure was reduced by the proportion of pathogen occurrence in drain samples (e.g. 67% occurrence for Norovirus and 50% for Giardia). Giardia concentrations were converted from genome copies to cysts assuming 16 GC/cyst.[28] QRMA assumptions were applied based on the dose response and probability of illness in Table S14 for three cases of drain concentration based on different septic tank use (Table S15).

Table S14. QRMA dose response inputs and probability of illness given infection

	Dose response models (from Foster et al. 2021, Table 2)	**Probability of illness given infection** (from Foster et al. 2021, Table S12)	
Norovirus GII	Fractional Poisson (P=0.722, μ=1106)[30]	0.55	18 of 33 infected individuals from norovirus GII challenge studies in the US were symptomatic [11,16]
Giardia	Exponential (k=5.72×10^{-2})[31]	0.4	A review of *Giardia* estimated that 60% of infected individuals are asymptomatic [32]. Among children 1-2 in Dhaka, probability of diarrhoea given *Giardia* infection = 0.47 [33]

Table S15. Comparison of the estimated annual probability of illness posed to children from exposure to open drains receiving different proportions of septic tank use.

Exposure cases (Drain concentration based on septic tank use)	Norovirus GII: Mean drain concentration (log_{10} GC /100mL)[a]	Norovirus GII: Mean Probability of illness per year[b]	*Giardia*[c]: Mean drain concentration (log_{10} GC /100mL)[a]	*Giardia*[c]: Mean Probability of illness per year[b]
100% septic tank use (Theoretical drain concentration based on septic tank effluent and greywater combined flow)	3.8	18%	2.9	3%
High septic tank use (Street A concentration, 81% population use septic tanks)	4.4	57%	3.9	44%
Low septic tank use (Street C concentration, 4% population use septic tanks)	5.3	98%	4.4	51%

Notes:

a. The inflows to the drains differ by the proportion of the population using septic tanks rather than direct discharge from toilets. The measured concentrations, excluding non-detects, were used to calculate the dose.

b. QMRA based on assumptions of 1mL drain water ingested during a child's exposure to open drains. Annual exposures were based on the survey, finding children play in drains 14 times per year. The exposure was reduced by the proportion of drain samples that tested positive for each pathogen, for example we assume that for each exposure only 67% would result in exposure to Norovirus GII and 50% to Giardia.

c. The concentration of Giardia as genome copy/100mL was converted to a concentration in cysts/100mL for the dose response calculations.

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Appendix B – Paper 3 supplementary materials

Appendix B – Paper 3 Supplementary Materials

Evidence to inform onsite well and sanitation siting criteria: Risk factors associated with well contamination in urban Indonesia

Site and response rate

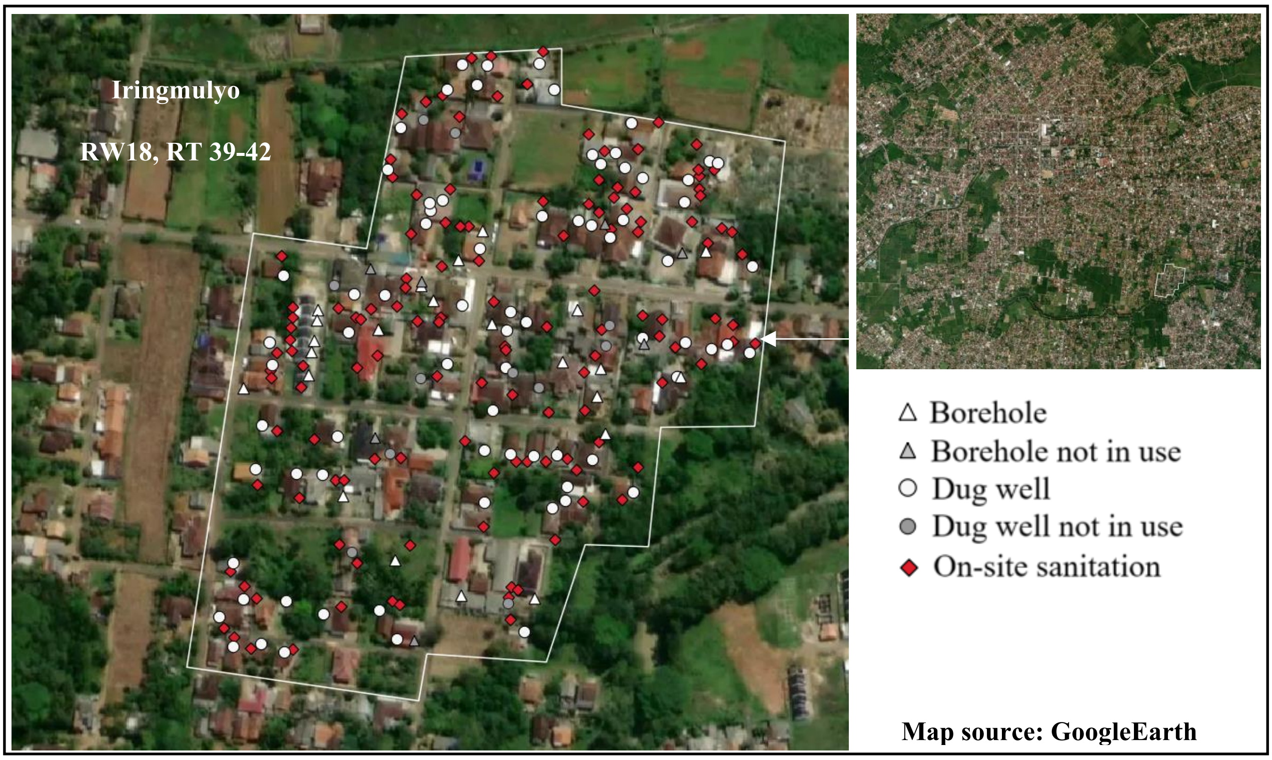


Figure S1: Map of survey site and location of mapped wells and sanitation systems. (Basemap from Google Earth earth.google.com/web/ accessed 11 August 2022).

Table S1: Summary of sampling response rate

Household survey		**Water supply**		**Well Sampling**	
Sample	132	Own groundwater supply	96	Water quality samples	96
Responded	112	Piped supply	2	- Boreholes	23
Unoccupied	7	Neighbours' groundwater supply	14	- Dug Wells	73
Refused	13	Multiple supplies	3	- Mixed supply (excluded from analysis)	1
Household survey		**Sanitation facilities**		**Well depth measured**	
Households	112	Own sanitation system	107	Dug wells	59
Population total	428	Neighbours system	5	Sanitation depth measured	31
Area (Ha)	8.7	Multiple sanitation systems	16		
Density (pp/km2)	492 0	Total sanitation systems in model	131		

Water quality results

Table S2. Water quality summary statistics for the three phases of sampling

E. coli MPN/100mL	Phase 1 9-12 Aug	Phase 2 1-4 Sept	Phase 3 21-23 Sept[a]	Total samples	Total wells[b]
n	96	96	92	284	
Mean	351	376	302	344	
Median	5.8	3.1	4.2	4.1	
StDev	754	788	687	743	
***E. Coli* contamination categories**					
<1 MPN	34%	42%	40%	39%	30%
1-100	36%	35%	33%	35%	
>100	29%	23%	27%	26%	36%

Notes a) Samples were taken at three intervals during what is considered dry season (early August, late August, mid September 2022) for all 96 wells, however in Phase 3 for four wells the last sample was not possible (two respondents absent, two pumps broken).
b) Total well results are wells that were negative across all samples (never tested positive), and wells that had *E. coli* >100MPN/100mL at least once across sampling rounds.

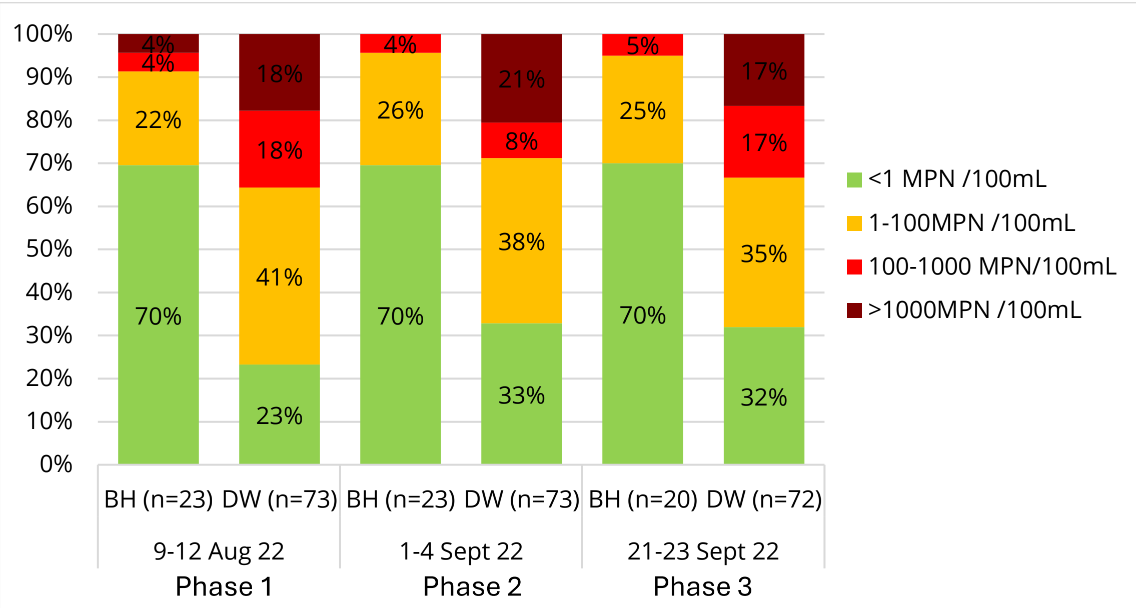


Figure S2. *E. coli* contamination categories per sample phase disaggregated by well type

Risk factors

Table S3: Pearsons bivariate correlation between well, environmental and sanitation factors

Well factors					
		Uses Bucket	Uncovered	No raised wall	Slab cracked-missing
Uses Bucket	Pearson Correlation	1	.389**	-.145	.080
	Sig. (2-tailed)		<.001	.159	.440
	N	96	96	96	96
Uncovered	Pearson Correlation			-.218*	.043
	Sig. (2-tailed)			.033	.674
	N			96	96
No raised wall	Pearson Correlation				-.007
	Sig. (2-tailed)				.945
	N				96
Environmental factors					
		Stagnant water	Unlined pond	Livestock	Other pollution
Stagnant water	Pearson Correlation	1	.706**	.324**	.200
	Sig. (2-tailed)		<.001	.001	.051
	N	96	96	96	96
Unlined Pond	Pearson Correlation			.279**	.157
	Sig. (2-tailed)			.006	.126
	N			96	96
Livestock	Pearson Correlation				.419**
	Sig. (2-tailed)				<.001
	N				96
Sanitation factors					
		Septic tank	Cistern flush	Sanitation system emptied	GW at ST more 2m
Septic tank (not pit latrine)	Pearson Correlation	1	-.043	.284**	-.313**
	Sig. (2-tailed)		.681	.006	.002
	N	96	94	94	96
Cistern flush (not pour)	Pearson Correlation			-.024	.128
	Sig. (2-tailed)			.817	.220
	N			94	94
Sanitation system emptied	Pearson Correlation				-.019
	Sig. (2-tailed)				.855
	N				94

** Correlation is significant at the 0.01 level (2-tailed).

GEE analysis of risk factors and well contamination

Table S4. Model scenarios

Model type	Variables included in model
1. Combined well, repeat measures	Categorical: Well type (borehole, covered dug well, uncovered dug well) Continuous: Groundwater depth Binary: Presence of livestock, presence of unlined pond, heavy rainfall during sampling, sanitation system within 10m
2. Dug well only, repeat measures	Categorical: Dug well type (covered, uncovered no bucket, uncovered with bucket for extraction) Continuous: Groundwater depth Binary: Presence of livestock, presence of unlined pond, heavy rainfall during sampling, sanitation system within 10m
3. Borehole only, repeat measures	Continuous: Groundwater depth, estimate borehole depth Binary: Presence of livestock, slab cracked or missing, heavy rainfall during sampling, sanitation system within 10m
4. Combined well, separate phases	Categorical: Well type (borehole, covered dug well, uncovered dug well) Continuous: Groundwater depth Binary: Presence of livestock, presence of unlined pond, sanitation system within 10m
Sanitation and groundwater variables assessed with each model	Groundwater depth: Depth to groundwater depth (continuous), Depth more than 2m. Distance: One sanitation system within 10m of well, Distance from well to closest sanitation system (continuous). Density: Two or more sanitation systems within 10m of well, count number of sanitation systems within 10m of well, Density of sanitation systems within 30m based on inverse density sum of reciprocal distance. Infiltration depth: Measured sanitation depth (model include variable of groundwater depth), Infiltration depth (below sanitation based, model excludes variable of groundwater depth) Sanitation type: Tank not pit, Cistern not pour flush

Table S5. Adjusted odds ratios of dug well only model binary logistic analysis using Generalized Estimating Equations comparing the association of base case risk factors and additional sanitation and groundwater variables with well contamination, considering a) presence of *E. coli* and b) high contamination (>100 MPN/100mL).

Parameter	>1 MPN/100mL			>100 MPN/100mL		
	Adjusted OR	95% CI	*p*	Adjusted OR	95% CI	*p*
Base model						
Dug well uncovered =2	0.292	0.49-10.76	2.296	0.469	0.32-11.67	1.940
Dug well covered =1	0.196	0.65-7.99	2.284	0.053	0.98-18.15	4.218
Borehole = 0						
Presence of unlined pond	0.726	0.41-3.59	1.213	0.639	0.28-2.2	0.781
Presence of livestock	0.460	0.54-3.98	1.459	**0.011**	1.38-12.19	**4.101***
Heavy rainfall phase	**0.025**	0.38-0.94	**0.595***	**0.002**	0.18-0.68	**0.353***
One sanitation facility within 10m of well	0.550	0.24-2.13	0.718	0.922	0.32-3.48	1.061
Depth to groundwater (m)	**0.009**	0.3-0.84	**0.501***	**0.000**	0.08-0.38	**0.174***
Additional variables added to base model						
Horizontal distance between sanitation system and well (n=96, *p*<0.013)						
One sanitation facility within 10m of well	0.718	0.24-2.13	0.550	1.061	0.32-3.48	0.922
Distance from well to closest sanitation system (m)	0.934	0.83-1.05	0.263	0.959	0.86-1.07	0.447
Density of sanitation systems around wells (n=96, *p*<0.008)						
Two or more sanitation facilities within 10m of well	4.225	0.75-23.87	0.103	3.502	1.2-10.25	0.022
Count of sanitation facilities within 10m of well	1.304	0.71-2.39	0.390	1.499	0.8-2.82	0.209
Density of sanitation systems within 30m of well	1.241	0.26-6.01	0.789	1.886	0.24-14.74	0.545
Sanitation type (n=96, *p*<0.013)						
Septic tank (not pit latrine)	0.381	0.12-1.24	0.109	0.455	0.11-1.87	0.274
Cistern flush (not pour flush)	0.303	0.08-1.18	0.086	0.510	0.1-2.71	0.430
Groundwater depth (n=96, *p*<0.013)						
Depth to groundwater (m)	**0.501**	0.3-0.84	**0.009***	**0.174**	0.08-0.38	**0.000***
Groundwater depth >2m	**0.383**	0.23-0.65	**0.001***	**0.264**	0.14-0.5	**0.000***

Infiltration depth [b] (n=28, *p* <0.013)						
Depth of sanitation system (m)	1.657	0.17-16.34	0.666	NA	NA	NA
Infiltration depth (m)	0.347	0.12-1.03	0.057	0.140	0.03-0.67	0.014

Notes: * significant association. For base model *p*<0.05. For the sanitation and groundwater variables assessed, the hypotheses with two variables assessed had an adjusted significance value of *p*<0.013, while sanitation density with three variables had an adjusted significance value of *p*<0.008. Note the dug well model includes 73 responses.

Table S6. Adjusted odds ratios of borehole only model binary logistic analysis using Generalized Estimating Equations comparing the association of base case risk factors and additional sanitation and groundwater variables with well contamination, considering a) presence of *E. coli* and b) high contamination (>100 MPN/100mL).

	>1 MPN/100mL		
Factors	Adjusted OR	95% CI	*p*
Base borehole model			
Slab cracked or missing	**5.029**	1.03-24.48	**0.045***
Presence of livestock	4.773	0.28-82.19	0.282
Heavy rainfall phase	1.626	0.28-9.45	0.588
One sanitation facility within 10m of well	0.332	0.04-2.94	0.321
Depth to groundwater (m)	1.346	0.34-5.34	0.673
Estimated borehole depth (m)	0.970	0.91-1.04	0.387
Additional sanitation and groundwater variables and factors			
Horizontal distance between sanitation system and well (n=96, *p*<0.013)			
One sanitation facility within 10m of well	0.332	0.04-2.94	0.321
Distance from well to closest sanitation system (m)	1.181	1.03-1.36	0.019
Density of sanitation systems around wells (n=96, *p*<0.008)			
Two or more sanitation facilities within 10m of well	0.841	0.08-9.30	0.887
Count of sanitation facilities within 10m of well	0.638	0.17-2.38	0.504
Density of sanitation systems within 30m of well	6.834	0.04-1052.1	0.455
Sanitation type (n=96, *p*<0.013)			
Septic tank (not pit latrine)	1.831	0.15-22.53	0.637
Cistern flush (not pour flush)	0.309	0.05-2.06	0.225
Groundwater depth (n=96, *p*<0.013)			
Depth to groundwater (m)	1.346	0.34-5.34	0.673
Groundwater depth >2m	0.940	0.09-10.09	0.959

Notes: * significant association. For base model *p*<0.05. For the sanitation and groundwater variables assessed, the hypotheses with two variables assessed had an adjusted significance value of *p*<0.013, while sanitation density with three variables had an adjusted significance value of *p*<0.008. Note the borehole model includes 23 responses only. There were insufficient borehole samples with high contamination, therefore only E. coli presence was modelled. Insufficient septic tank depth and infiltration samples related to boreholes resulted in an incomplete analysis with GEE.

Table S7. Adjusted odds ratios of for base models of individual phases from binary logistic analysis using Generalized Estimating Equations comparing the association of base case risk factors with well contamination, considering a) presence of *E. coli* and b) high contamination (>100 MPN/100mL).

Parameter	Combined with repeats (all phase)		Phase 1		Phase 2		Phase 3	
	AOR	*p*	AOR	*p*	AOR	*p*	AOR	*p*
>1 MPN/100mL								
Dug well uncovered =2	7.370	**0.000***	10.182	**0.000***	7.140	**0.003***	5.491	**0.012***
Dug well covered =1	3.295	0.053	4.225	**0.048***	1.886	0.359	3.276	0.139
Borehole = 0								
Presence of unlined pond	1.069	0.893	0.825	0.748	1.082	0.892	1.402	0.597
Presence of livestock	1.681	0.257	1.376	0.570	2.013	0.190	1.785	0.263
One sanitation facility within 10m of well	0.755	0.544	1.189	0.742	0.398	0.098	0.699	0.500
Groundwater depth (m)	0.559	**0.012***	0.548	0.069	0.812	0.511	0.425	**0.011***
>100 MPN/100mL								
Dug well uncovered =2	9.140	**0.016***	7.293	**0.045***	7.298	0.082	8.162	0.114
Dug well covered =1	3.343	0.233	2.215	0.447	4.306	0.217	3.595	0.353
Borehole = 0								
Presence of unlined pond	0.811	0.677	0.399	0.177	2.082	0.267	1.134	0.858
Presence of livestock	3.872	**0.008***	3.771	**0.028***	4.468	**0.034***	4.771	**0.036***
One sanitation facility within 10m of well	1.276	0.666	1.997	0.336	0.433	0.245	1.395	0.666
Groundwater depth (m)	0.226	**0.000***	0.213	**0.000***	0.201	**0.004***	0.139	**0.000***

Notes: * significant association. For base model $p<0.05$.

Table S8. Adjusted odds ratios for individual phases from binary logistic analysis using Generalized Estimating Equations comparing the association of different sanitation and groundwater risk factors with well contamination, considering a) presence of *E. coli* and b) high contamination (>100 MPN/100mL).

Parameter	Repeat (combined)		Phase 1		Phase 2		Phase 3	
	AOR	*p*	AOR	*p*	AOR	*p*	AOR	*p*
>1 MPN/100mL								
Distance (p<0.013)								

One sanitation facility within 10m of well	0.755	0.544	1.189	0.742	0.398	0.098	0.699	0.500
Distance from well to closest sanitation system (m)	0.977	0.575	0.945	0.423	1.008	0.898	0.975	0.683
Density (p<0.008)								
Two or more sanitation facilities within 10m of well	2.274	0.143	2.216	0.287	1.898	0.272	3.021	0.123
Count of sanitation facilities within 10m of well	1.174	0.538	1.367	0.337	0.911	0.743	1.237	0.475
Density of sanitation systems within 30m of well	1.680	0.446	18.722	0.096	0.421	0.528	7.266	0.235
Sanitation type (p<0.013)								
Septic tank (not pit latrine)	0.459	0.149	0.342	0.095	0.441	0.204	0.569	0.456
Cistern flush (not pour flush)	0.570	0.320	0.501	0.309	0.551	0.323	0.711	0.594
Groundwater (p<0.013)								
Groundwater depth (m)	0.559	**0.012***	0.548	0.069	0.812	0.511	0.425	**0.011***
Groundwater depth >2m	0.561	**0.021***	0.240	0.053	0.584	0.395	0.413	0.134
Infiltration depth (p<0.013)								
Depth of sanitation system (m)	0.736	0.656	1.038	0.976	0.142	0.112	1.020	0.981
Infiltration depth (m)	0.799	0.618	0.433	0.367	1.899	0.478	0.602	0.378
>100 MPN/100mL								
Distance (p<0.013)								
One sanitation facility within 10m of well	1.276	0.666	1.997	0.336	0.433	0.245	1.395	0.666
Distance from well to closest sanitation system (m)	0.942	0.237	0.935	0.307	1.007	0.949	0.908	0.226
Density (p<0.008)								
Two or more sanitation facilities within 10m of well	3.098	**0.026***	4.870	**0.030***	0.656	0.509	3.889	0.116
Count of sanitation facilities within 10m of well	1.570	0.123	1.880	0.113	0.576	0.223	1.923	0.167
Density of sanitation systems within 30m of well	2.113	0.451	2.915	0.545	0.178	0.567	86.513	**0.026***
Sanitation type (p<0.013)								
Septic tank (not pit latrine)	0.416	0.211	0.148	**0.041***	0.620	0.572	0.326	0.304
Cistern flush (not pour flush)	0.716	0.632	1.084	0.918	0.345	0.275	0.510	0.511
Groundwater (p<0.013)								
Groundwater depth (m)	0.226	**0.000***	0.213	**0.000***	0.201	**0.004***	0.139	**0.000***
Groundwater depth >2m	0.279	**0.001***	0.226	**0.028***	0.146	**0.005***	0.074	**0.000***
Infiltration depth (p<0.013)								
Depth of sanitation system (m)	0.226	**0.000***	0.213	**0.000***	0.201	**0.004***	0.139	**0.000***
Infiltration depth (m)	NA		NA		0.000	**0.010***	0.207	0.071

Notes: The findings in bold are those that are significant. The hypotheses with two variables assessed had an adjusted significance value of p<0.013, while sanitation density with three variables had an adjusted significance value of p<0.008.

Appendix C – Paper 4 supplementary materials

Appendix C – Paper 4 Supplementary Material

Indicators to complement global monitoring of safely managed on-site sanitation to understand health risks: Supplementary information

Descriptive results of cities and districts

Supplementary Table 1. Summary of city characteristics

			Background characteristics from survey results			
Country and city	**Household sample size**	**City population[a]**	**% on-site sanitation[b]**	**Average depth groundwater**	**% drinking supply from groundwater**	**Main soil type[c]**
URBAN CITIES	**26,436**					
Bangladesh	**11,995**	(2022)				
Benapole	1270	36,524		3-5m	95%	Clay
Gazipur	463	5,433,563	100%	>20m	5%	Clay
Jessore	1543	3,147,039	100%	5-10m	96%	Clay
Jhenaidah	1872	2,051,607	100%	5-10m	68%	Gravel and sand
Khulna	2912	2,673,002	100%	5-10m	52%	Peat and clay
Kushtia	2703	2,198,731	100%	3-5m	39%	Clay
Tongi	1232	350,000 (2011)	100%	>20m	2%	Clay
Indonesia	**5,038**	(2020)				
Bandar Lampung	2413	1,166,066	100%	10-20m	29%	Gravel, clay, peat
Metro	1069	168,676	100%	5-10m	74%	Clay
Tasikmalaya	1556	716,155	100%	3-5m	49%	Gravel and sand
Nepal	**2,960**	(2021)				
Birendranagar	1087	153,863	100%	5-20m	16%	Clay
Chandannath	393	21,036	100%	>20m	0%	Clay
Khadak	392	52,778	100%	5-20m	98%	Clay
Nepalgunj	1088	164,444	100%	2-3m	92%	Fine sand
Tanzania	**3,613**	(2022)				
Arusha	2507	617,631	97%	1-3m	5%	Clay
Shinyanga	1106	139,727	100%	2-5m	3%	Clay
Zambia	**2,830**	(2010 - district)				
Kabwe	1121	202,360	66%	1-3m	46%	Fine sand and gravel
Kasama	636	231,824	96%	10-20m	25%	Clay and gravel
Mbala	271	203,129	95%	2-20m	18%	Clay
Mpulungu	395	98,073	99%	3-5m	46%	Gravel, sand and fractured rock
Nakonde	407	119,708	100%	5-10m	86%	Clay
RURAL DISTRICTS	**5,348**					
Bhutan	**2,620**	(2017)				
Chhukha	464	68,966	100%	>10m	11%	Clay
Dagana	303	24,965			1%	
Lhuentse	137	14,437			0%	
Pemagatshel	177	23,632			0%	
Punakha	362	28,740			0%	
Samtse	598	62,590			2%	
Trashigang	386	45,518			0%	
Zhemgang	193	17,763			1%	
Laos	**1,945**	(2015)				
Atsaphone	552	59,580	100%	1- >10m	82%	Clay
Champhone	994	109,174		1-10m	17%	Sand, gravel, clay
Phalanxay	399	40,097		1-5m	51%	Gravel
Nepal	**783**	(2021)				
Dailekh	315	252,313	100%	>10m	10%	Clay
Sarlahi	468	862,470		2-3m	100%	Clay

a. Population from http://www.citypopulation.de/
b. % of surveyed population using on-site sanitation (septic tanks and latrines) of improved sanitation (on-site and sewer).
c. Soil type: Clay = Heavy clay/loam, Gravel = gravel or course sand,

Summary of sanitation data

Summary of the country data for the global indicator ladder of sanitation. Please note that while the safely managed sanitation estimate for the global monitoring is only based on those that do not share their facilities (at least basic) the analysis in the paper was based on improved OSS, as it was for the purpose of comparison of impact rather than global reporting against SDG.

Supplementary Table 2. Sanitation ladder based on global indicators and showing pit type.

	Urban					Rural			Average all countries
	Bangladesh	Indonesia	Nepal	Tanzania	Zambia	Bhutan	Laos	Nepal	
Open Defecation	0%	4%	7%	3%	3%	4%	52%	4%	10%
Unimproved	11%	19%	1%	9%	18%	9%	0%	0%	8%
Improved (Sewer)	0%	0%	0%	2%	10%	0%	0%	0%	1%
Improved (OSS)	89%	77%	93%	87%	68%	87%	48%	96%	81%
- Improved and contained OSS	37%	63%	87%	84%	67%	82%	45%	92%	70%
- Improved and emptied OSS	36%	8%	14%	11%	2%	2%	10%	11%	12%
Limited	22%	5%	15%	29%	18%	8%	5%	4%	13%
Basic Sewer	0%	0%	0%	1%	10%	0%	0%	0%	1%
Basic OSS	67%	72%	78%	59%	51%	79%	42%	92%	68%
- Basic and contained	29%	59%	72%	57%	50%	79%	42%	91%	60%
- Basic, contained and emptied	10%	5%	9%	5%	1%	2%	4%	10%	6%
- Basic contained and stored in-situ	19%	54%	64%	48%	49%	77%	38%	82%	54%
Containment of improved OSS (% respondents)									
Uncontained OSS	52%	17%	11%	7%	5%	0%	3%	8%	14%
Contained OSS	31%	60%	81%	79%	63%	81%	42%	85%	66%
Emptying of improved OSS (% respondents)									
Previously emptied	32%	6%	13%	10%	1%	2%	4%	10%	10%
Never emptied or don't know	55%	69%	79%	66%	63%	80%	40%	83%	67%
Built a new pit	1%	2%	1%	5%	1%	0%	0%	0%	1%

Supplementary Table 3. Type of improved sanitation

Type of improved sanitation	Urban					Rural			Average all countries
	Bangladesh	Indonesia	Nepal	Tanzania	Zambia	Bhutan	Laos	Nepal	
Direct pit	6%	4%	2%	32%	57%	12%	9%	7%	16%
Off-set pit	22%	10%	51%	40%	6%	71%	29%	84%	39%
Double (alternating) off-set pit	5%	0%	4%	2%	1%	1%	53%	0%	8%
Two (or more) sequential pits	15%	0%	1%	0%	0%	0%	7%	1%	3%
Single compartment (for composting and UDTs)	0%	0%	0%	3%	1%	0%	0%	0%	0%
Water tight tank	3%	1%	29%	2%	0%	16%	1%	7%	7%
Septic tank	47%	79%	13%	18%	21%	0%	0%	1%	23%
Communal septic tank	1%	6%	0%	1%	1%	0%	0%	0%	1%
Piped sewer or DEWATS	0%	0%	0%	2%	13%	0%	0%	0%	2%

Supplementary Table 4. Key context variables for each country for improved on-site sanitation systems

	Urban					Rural		
	Bangladesh	Indonesia	Nepal	Tanzania	Zambia	Bhutan	Laos	Nepal
% Poorer households (Lowest two wealth quintiles)	32%	6%	6%	1%	35%	35%	7%	29%
% GW depth less than 5m	34%	19%	39%	92%	41%	0%	67%	62%
% Dry containment (not water-based/wet)	5%	0%	1%	17%	62%	8%	1%	1%
% Pit (not tank)	49%	14%	59%	79%	74%	84%	98%	92%
% Age toilet more than 5 years	67%	77%	60%	47%	28%	48%	58%	39%
% Depth containment less than 3m	4%	31%	59%	1%	23%	57%	35%	27%

Supplementary Table 5. Comparison of average pit/tank depth between cities

	% OSS with depth estimate	Depth of tank/pit raw data				% High confidence in self-reported	Infiltration depth (Groundwater level – containment depth)	
		Average	Min	Max	St Dev		Average	St Dev
Bangladesh	89%	8.2	0.5	45	4.9	26%	2.8	6.6
Indonesia	92%	3.0	1.0	200	4.7	46%	9.8	6.1
Nepal	99%	2.4	1.0	4	0.6	65%	10.6	10.1
Tanzania	95%	12.0	2.0	83	7.5	46%	-4.9	3.6
Zambia	80%	3.3	1.0	20	1.9	28%	7.9	9.7
Bhutan	100%	2.39	1	20	0.6	NA	17.6	0.6
Laos	100%	2.11	1	10	0.7	NA	4.3	5.3
Nepal	100%	2.89	1	5	0.8	NA	6.6	8.6

Supplementary Table 6. Urban timely emptying threshold per country and containment type

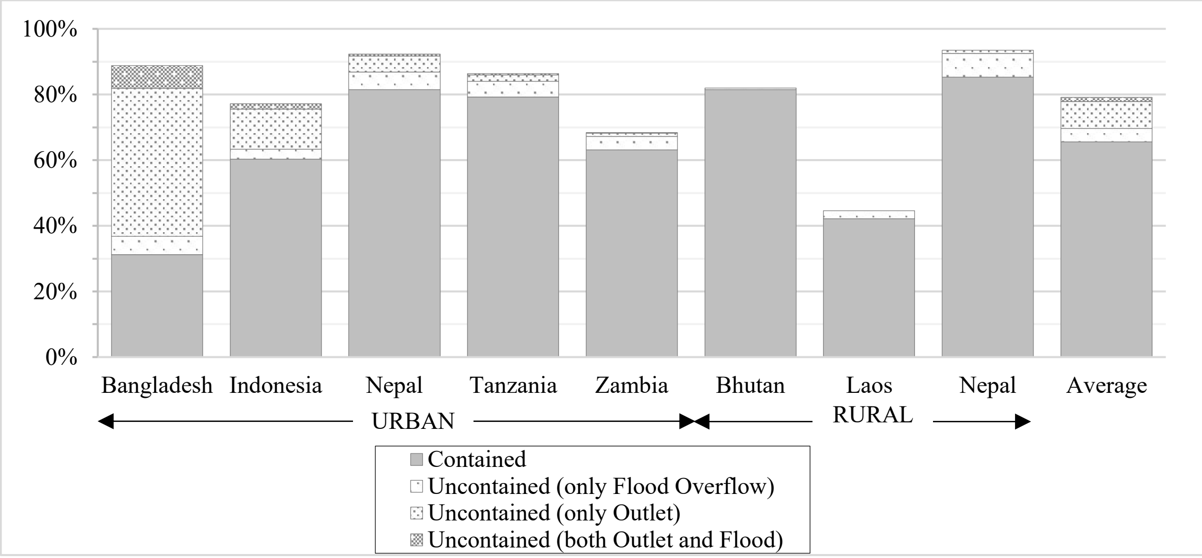
		Bangladesh		Indonesia		Nepal		Tanzania		Zambia	
	HH members	4.8		4		6		5		4.1	
Type	Accumulation rate (m3 /cap / year)	Final size (m3)	Thres-hold Years	Final size (m3)	Thres-hold Years	Final size (m3)	Thres-hold Years	Final size (m3)	Thres-hold Years	Final size (m3)	Thres-hold Years
Pit (direct or off-set)	0.06	1.57	5.5	1.57	6.5	1.57	4.4	2.36	7.9	5.6	22.8
Twin pits (sequential)	0.06	3.14	10.9	3.14	13.1	3.14	8.7	4.72	15.7	11.2	45.5
Twin pits (alternating)	0.06	1.57	5.5	1.57	6.5	1.57	4.4	2.36	7.9	5.6	22.8
Dry / composting (single compartment)	0.04	0.12	0.6	0.12	0.8	0.12	0.5	0.12	0.6	0.12	0.7
Dry / composting (double compartment)	0.04	0.24	1.3	0.24	1.5	0.24	1.0	0.24	1.2	0.24	1.5
Septic tank, holding tank	0.08	7.5	19.5	1.8	5.6	7.5	15.6	1.26	3.2	8.3	25.3

Supplementary Table 7. Rural timely emptying threshold per country and containment type

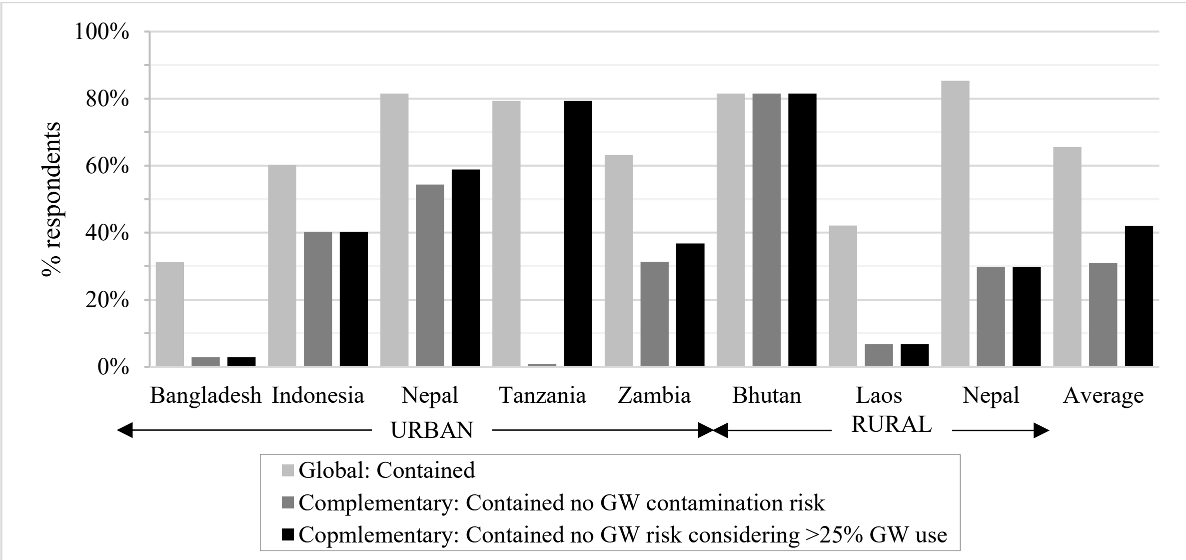
		Bhutan		Laos		Nepal	
	HH members	4		5		6	
Type	Accumulation rate (m3/cap/year)	Final size (m3)	Threshold Years	Final size (m3)	Threshold Years	Final size (m3)	Threshold Years
Pit (direct or off-set)	0.06	2.10	8.8	1.26	4.2	1.57	4.4
Twin pits (sequential)	0.06	4.21	17.5	2.51	8.4	3.14	8.7
Twin pits (alternating)	0.06	2.10	8.8	2.51*	8.4*	1.57	4.4
Dry / composting (single compartment)	0.04	0.12	0.8	0.12	0.6	0.12	0.5
Dry / composting (double compartment)	0.04	0.24	1.5	0.24	1.2	0.24	1.0
Septic tank, holding tank	0.08	7.5	19.5	6	15.0	7.5	15.6

* Note that Laos considered the volume of alternating pits equivalent to sequential pits which differs from other countries.

Complementary indicator further analysis by country



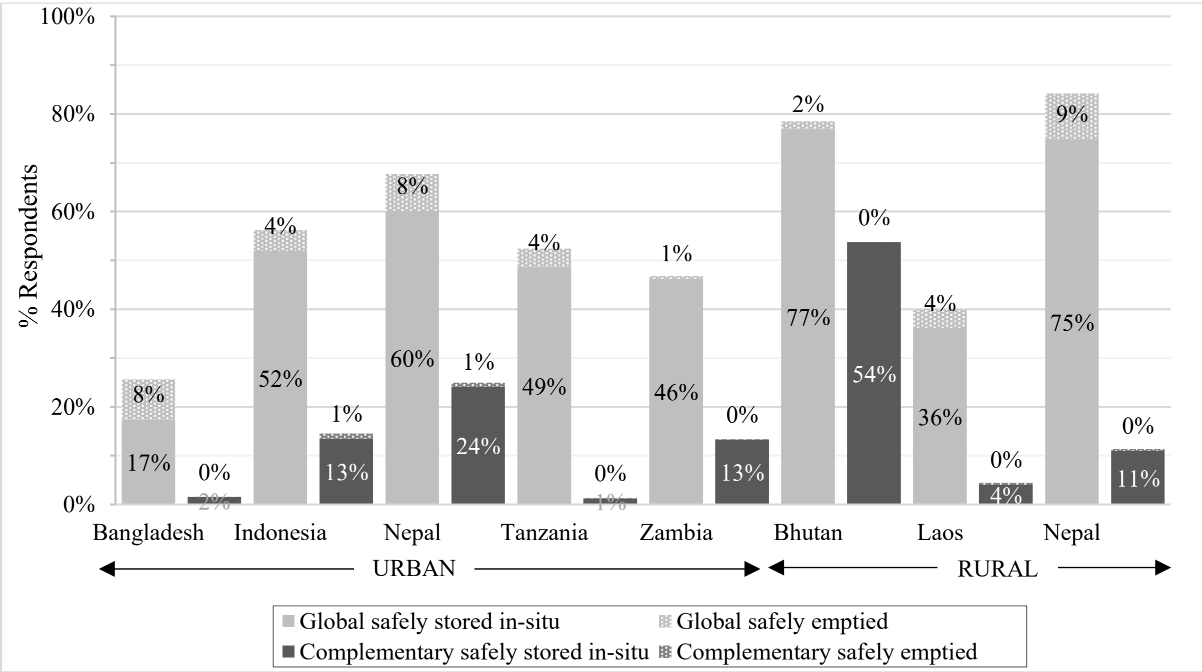
Supplementary Figure 1. Assessment of the global indicator for containment highlighting the fraction of uncontained due to outlets vs. overflow. Outlets to surface environment were a major containment risk in Bangladesh and Indonesia, while overflow was common across countries.



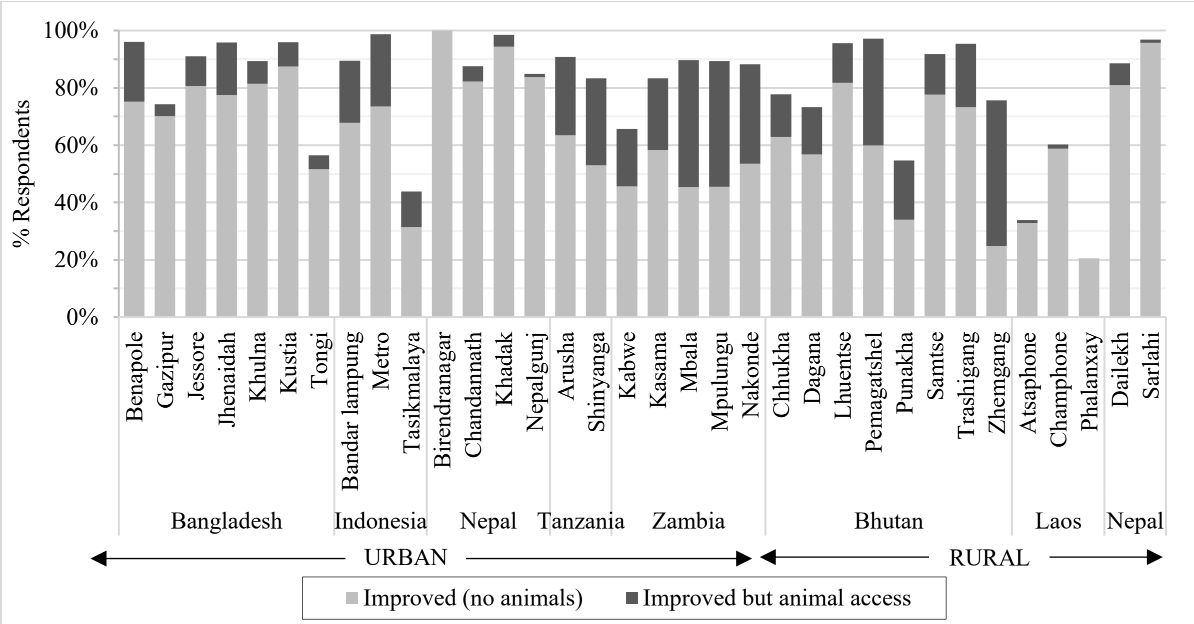
Supplementary Figure 2. Comparison of global indicator for containment, the proposed complementary indicator of groundwater contamination risk and an alternative complementary indicator of contamination risk only where groundwater use was reported by more than 25% of the population. The alternative indicator demonstrates containments in Tanzania pose a risk of groundwater contamination, but this is less of a health risk due to groundwater not being used for drinking.

Supplementary Table 8. Variation in the impact of complementary indicators between and within countries

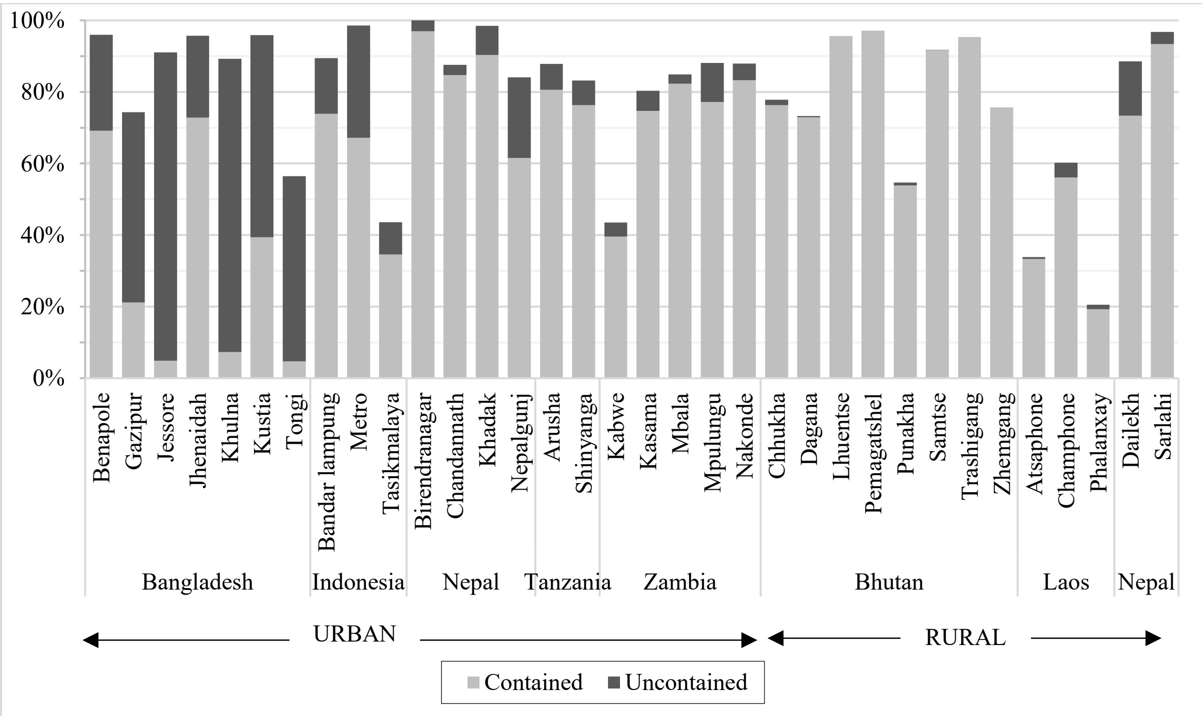
	% respondents (country average)		Between countries variation in difference between global and complementary indicators		Within-country variation (difference in global and complementary indicators for each city/district)	
	Global	Global + Complementary	St. Dev	Range of differences (min to max)	Average of country St Dev (range of St Dev)	Range of city/district differences showing examples of largest and smallest range
Animals access	81%	66%	12%	1-29%	6% (2-13%)	14-51% in Bhutan, 0-2% in Laos
Groundwater risk	66%	31%	24%	0-78%	23% (0%-66%)	0-93% rural Nepal, 0% Bhutan
Overdue for emptying	67%	45%	10%	8-42%	11% (4-17%)	11-44% urban Nepal, 14-25% Tanzania
Entered to empty	10%	8%	2%	0-5%	0.5% (0-1.1%)	2-5% Bangladesh, 0-0.5% Zambia
Inadequate PPE to empty	10%	3%	9%	1-29%	4% (0-11%)	11-43% Bangladesh, 0-1% Zambia



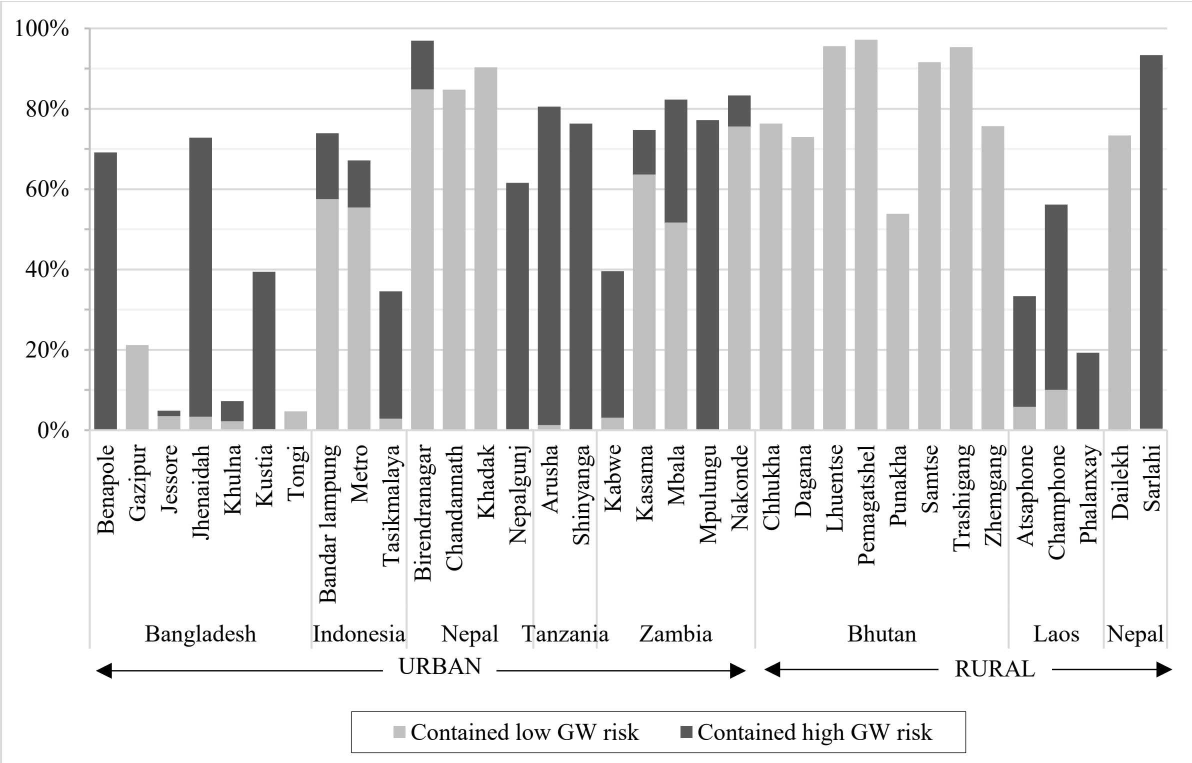
Supplementary Figure 3. Country comparison of the cumulative estimate of safely managed on-site sanitation across the service chain (excluding transport and treatment) for the global and complementary indicators disaggregated by those stored in-situ (safely managed) and those emptied (potentially safely managed).



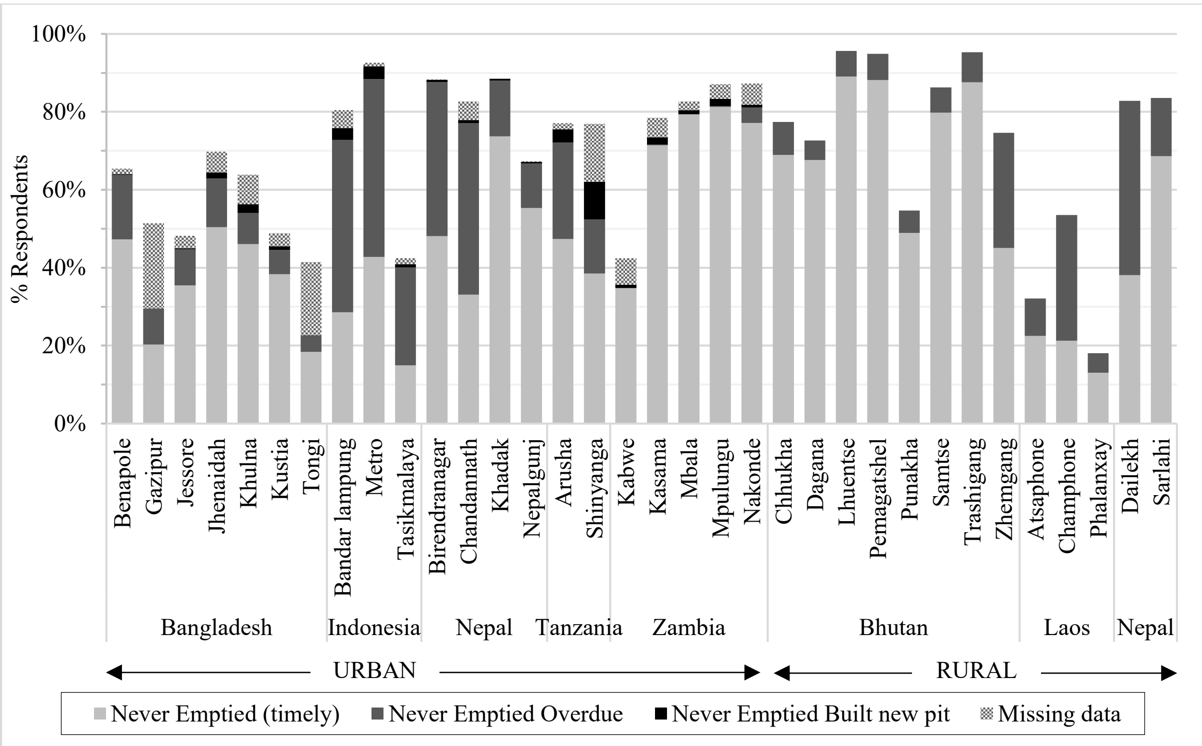
Supplementary Figure 4. Comparison of global indicator for improved sanitation and complementary indicator for no animal access to improved sanitation facilities by city or district. Light grey shows the complementary indicator of improved sanitation without animal access, with animal access to improved sanitation facilities shown in dark. The total column height is equivalent to the global indicator for improved sanitation.



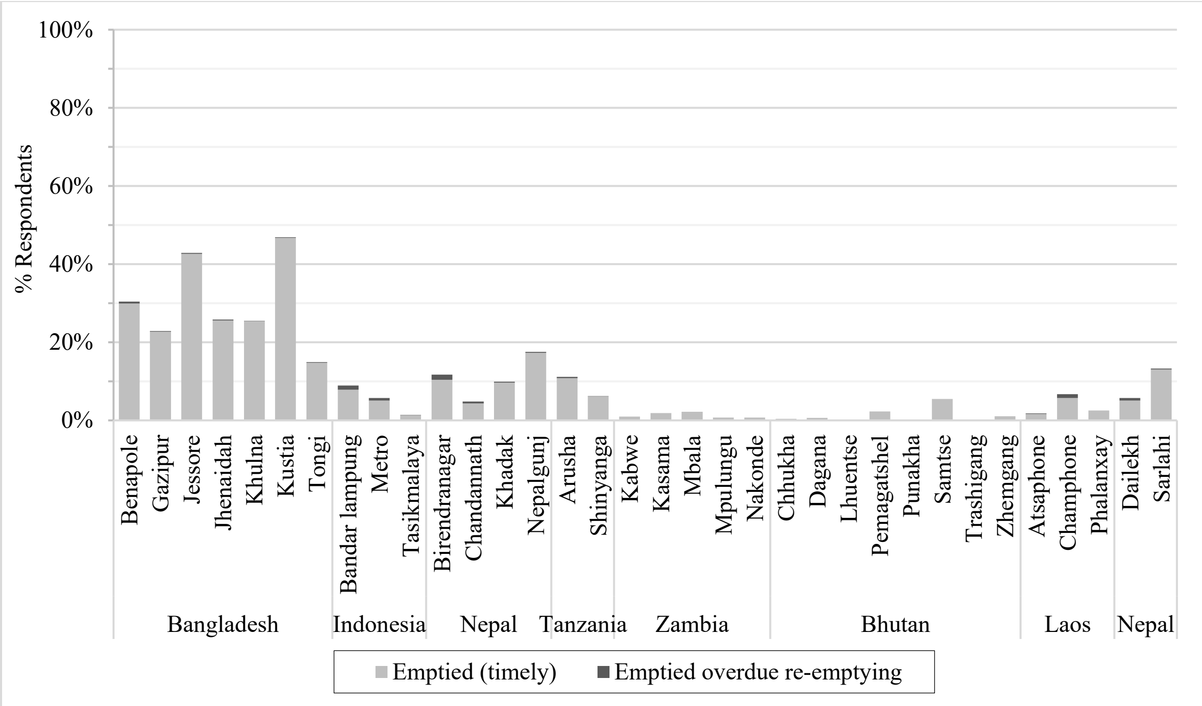
Supplementary Figure 5. Global indicator for contained on-site sanitation demonstrating the proportion contained in light grey and the uncontained in dark grey (outlet to surface environment and/or flooding and overflow). The total column height equals the proportion of respondents with improved on-site sanitation.



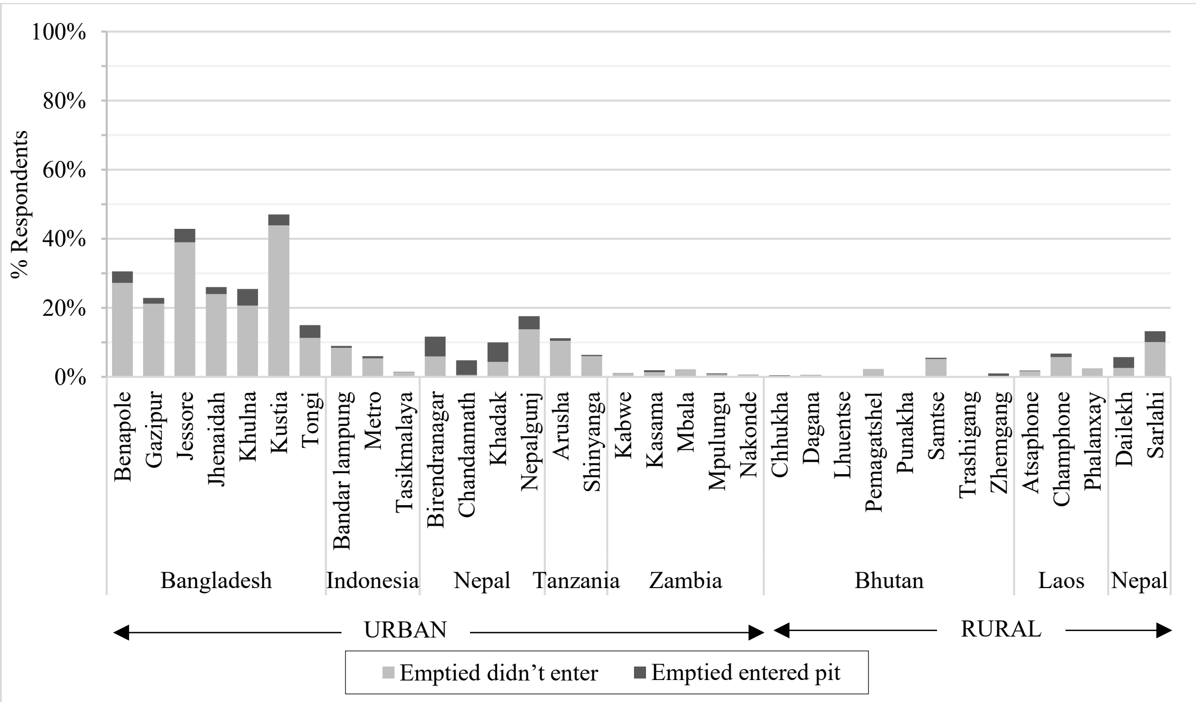
Supplementary Figure 6. Comparison of global indicator for contained on-site sanitation and the complementary indicator for a contained system with a low risk of groundwater contamination by city and district. Light grey shows the complementary indicator of contained sanitation with a low risk of groundwater contamination. High contamination risk is shown in dark. The total column height is equivalent to the global indicator for contained sanitation.



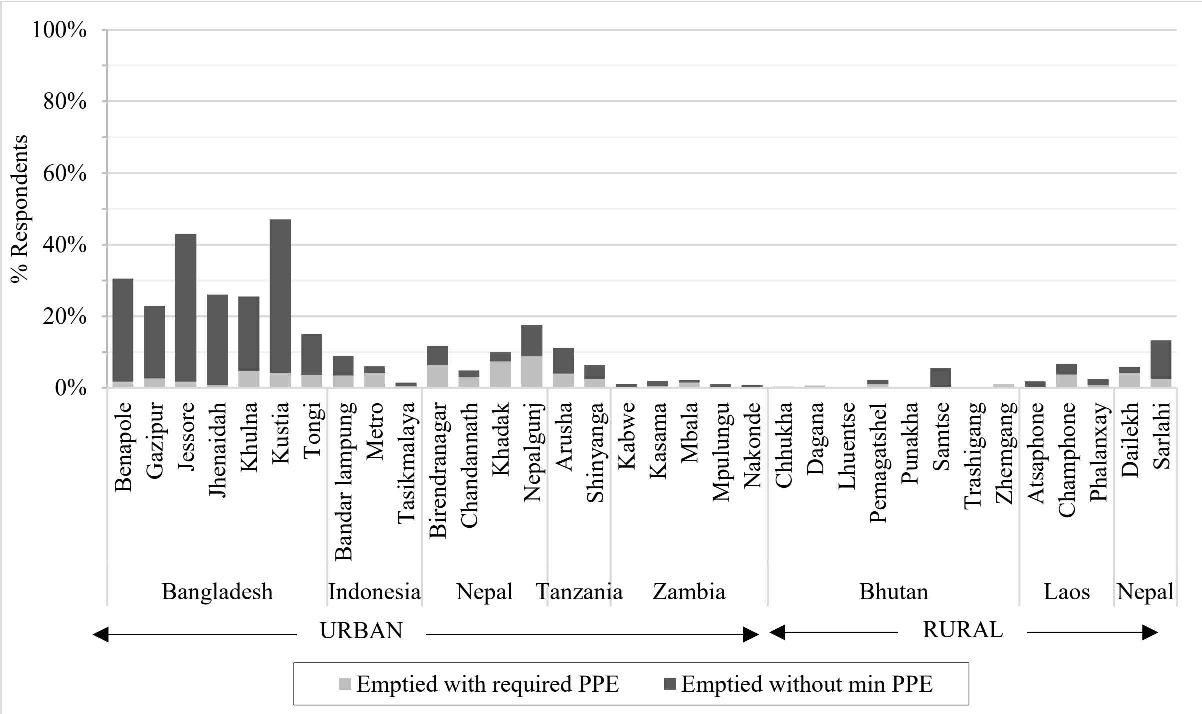
Supplementary Figure 7. Comparison of the global indicator for never emptied (safely stored in-situ) and the complementary indicator considering the timely emptying threshold. Light grey shows the complementary indicator of improved never emptied OSS that are below the emptying threshold, with the dark grey those overdue for emptying. Black indicates the respondents reporting they had never emptied but built a new pit and the pattern is missing data on emptying or age of operation.



Supplementary Figure 8. Comparison of global and complementary indicator for timely emptying of emptied containments. Light grey shows the complementary indicator of improved, emptied on-site sanitation not exceeding the timely threshold, with the systems overdue for re-emptying shown in dark. The total column height is equivalent to the global indicator for emptied sanitation.



Supplementary Figure 9. Comparison of the global indicator for emptying improved on-site sanitation and the complementary indicator for emptying without entering the containment by city or district. Light grey shows the complementary indicator of emptied containments that were not entered, with the systems entered to empty shown in dark. The total column height is equivalent to the global indicator for emptied sanitation.



Supplementary Figure 10. Comparison of the global indicator for emptying improved on-site sanitation facilities and complementary indicator on emptying with adequate PPE by city or district. Light grey shows the complementary indicator of emptied containments that reported adequate use of PPE, with the systems without adequate PPE shown in dark. The total column height is equivalent to the global indicator for emptied sanitation.

Questionnaire used in the urban baseline data collection

Supplementary Table 9. Detailed questions and responses from SNV urban sanitation survey used in this analysis

Indicator	Question	Responses
Overarching questions	Do members of your household have a toilet?	No toilet, practice OD No own toilet, use of shared toilet (or neighbour's) Use of communal toilet Use of one cubicle in a communal toilet block Use of own household toilet
	Ask and observe question: What type of toilet is it? Can you please show it to me? (*only answer if above indicates use of a toilet)*	Pour flush toilet Cistern flush toilet Ventilated improved pit latrine (VIP) Pit latrine with slab Pit latrine without slab Composting toilet Urine diversion toilet (UDT) Bucket Hanging toilet or hanging latrine
	Ask and observe question: Where do the faeces go? (*Only answer if above was an improve toilet or pit latrine without slab)*	To the street- field or open pit To a pond To the river, waterway or open drain To a closed drain To a direct pit To an off-set pit To a double (alternating) off-set pit To two (or more) sequential pits To a single compartment (for composting and UDTs) To a double compartment (for composting and UDTs) To a water tight tank To a septic tank To a communal septic tank To piped sewer or DEWATS
	Ask and observe question: Is there an effluent outlet? (*Only answer if above response was a containment)*	Yes No
	Ask and observe question: Where does the effluent go? (*Only answer if you responded Yes to above)*	To the street or open field To an uncovered drain To a covered drain To a water stream

Indicator	Question	Responses
		To soak pit or soak well To sewer or other piped system
Animal access to excreta: Rats and flies cannot enter and exit the toilet or containment	Can rats access the faeces in any way? *Only answer if have or use a toilet*	Yes No
	Does the toilet pan or slab allows flies to enter and exit the pit? *(Note only asked to those that responded no to the first one, as access to rats means flies could also enter)*	Yes No
Flooding and overflow*: Pit or tank does not flood, overflow or leak	Does the toilet flood at any time of the year? (*Note this was not included in rural surveys*)	Yes No
	Does the pit or toilet leak, overflow or flood at any time of the year?	Yes, sewage backflows into the toilet or property Yes, the pit is leaking into the property Yes, the pit is overflowing or impossible to flush No, sewer works well No, pit or tank works well Don't know
	How often does it leak or overflow? *(Note only asked to those that responded yes to leak, overflow or flood)*	It happened only once When there is a very heavy rain Regularly during the rainy season Continuously Don't know
Groundwater risk: Low risk to groundwater from subsurface leaching of pits or tanks	How deep is the toilet pit below the surface? *(Note this is asked to all pits/tanks, indicating depth should be from surface to base on pit or tank.)*	m
	What is the main source for drinking water?	Piped into dwelling Piped to yard/plot Communal tap Tanker truck Cart with small tank River/stream Pond/lake/dam Rainwater Surface water (river/dam/ lake/pond/stream/canal/ irrigation channel) Bottled water Tube well or borehole Protected well Unprotected well Protected spring Unprotected spring Protected public well/borehole Spring
	Local government question: What is the predominate soil type in the neighbourhood / sub-district?	Solid rock Peat Heavy clay/loam Fine sand Gravel or coarse sand Fractured rock
	Local government question: What is the typical depth of groundwater in the neighbourhood / sub-district?	Less than 1 metre Between 2-3 metres Between 3-5 metres Between 5-10 metres Between 10-20 metres More than 20 metres
Not emptied OSS within timely threshold: Never emptied pits or tanks, age below timely emptying threshold **Emptied OSS within timely threshold:** Years since pits or tanks were emptied within timely emptying threshold	How old is your toilet (pit/tank)?	Less than 1 year 1-3 years 4-5 years Older than 5 years Don't know
	Has the pit or tank ever been emptied?	Yes No- the pit is not full yet No- we have already dug a new pit No, it is a sewer connection Don't know
	When was the last time the pit or tank was emptied? (if emptied)	Less than 6 months ago 6- 12 months ago 1-3 years ago 4-10 years ago More than 10 years ago Don't know
	Do you share this toilet with people who are not a member of your household?	No, only used by own household Yes, with neighbour's household Yes, with more than two households
Emptying health and safety risks: Emptying of containments does not pose a health and safety risk to workers or the public	To empty the pit, did someone need to enter the pit?	Yes No Don't know
	Did you observe any of the following safter measures during emptying? (use of boots, gloves and a mask)	Workers were wearing boots and gloves Workers were wearing face masks Workers cleaned up any spills before they left Workers washed hands with water and soap before they left Vehicle was well closed and not leaking None of the above Don't know