



Mst Sufia Sultana

**SPATIAL REPRESENTATION OF FAECAL POLLUTION IN
UNSEWERED URBAN CATCHMENTS**

CRANFIELD WATER SCIENCE INSTITUTE
PhD Water

PhD
Academic Year: 2019 - 2023

Supervisor: Professor Sean Tyrrel
Associate Supervisor: Dr Toby Waine
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This thesis is submitted in partial fulfilment of the requirements for
the degree of PhD

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ABSTRACT

In many secondary cities in Bangladesh and other economically developing regions in Asia, Africa and Latin America, urban sanitation is dependent on individually constructed and maintained decentralised sanitation technologies, e.g., septic tanks operating in the absence of a city-wide support system. In such urban areas, wastewater is transported through a network of storm drains which were not designed for this purpose. The release of wastewater runs the risk of imperfect containment and high risk of exposure to faecal pathogens. Effective methods to identify the sources and movement pathways of faecal matter within cities are currently lacking. Here, a SanIFFlow approach is introduced, representing a novel methodology that utilises open-source data to map the sanitation infrastructure and the faecal matter sources and movement pathways. This approach is first demonstrated through a prototype sub-catchment model within Rajshahi city, Northwest Bangladesh. The sub-catchment model identifies and characterises the sources, pathways, and movement of faecal matter. To refine and validate the method, an uncertainty analysis was conducted, supplemented by a field study, to assess the reliability of the approach. Sensitivity analysis identified five key factors influencing the spatial pattern of faecal flow: septic tank emptying, soak pit use, sludge removal from drains, variations in faecal matter production, and the absence of toilets in some buildings. While each factor might have a negligible impact individually, in combination the factors showed almost 50% faecal matter cannot reach the outlet point. Further insights from the uncertainty analysis and fieldwork suggest that, although the sub-catchment model has potential for individual building level sanitation management, the existing ward-level management system, being the smallest administrative unit in the case study city, calls for a model at that spatial scale as a more practical approach. Building upon this, the SanIFFlow approach has been deployed to develop a city-scale model built from ward-level subunits, tailored for practical application in unsewered cities like Rajshahi. This approach holds promise for global applicability, given the widespread availability of open-source data.

Keywords:

Sanitation, Faecal sludge, Open-source data, Bangladesh, Mapping, Secondary city

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LIST OF ABBREVIATIONS

ALOS	Advanced Land Observing Satellite (ALOS) Phased Array type
PALSAR	L-band Synthetic Aperture Radar (PALSAR)
ASF DAAC	Alaska Satellite Facility Distributed Active Archive Data Center
BNBC	Bangladesh National Building Code
CLUES	Community-Led Urban Environmental Sanitation
CWIS	City Wide Inclusive Sanitation
DEM	Digital Elevation Model
EPSRC	Engineering and Physical Science Research Council
FSM	Faecal Sludge Management
GIS	Geographic Information Systems
GPS	Global Positioning System
HCES	Household-Centred Environmental Sanitation
LiDAR	Light Detection and Ranging
LMICs	Low- and Middle-Income Countries
MDG	Millennium Development Goals
NASA	National Aeronautics and Space Administration
NGOs	Non-governmental Organisations
ODF	Open Defecation Free
OSM	OpenStreet Map
RWASA	The Rajshahi Water Supply and Sewerage Authority
SanIFFlow	Sanitation Infrastructure and Faecal Flow
SDG	Sustainable Development Goal
SFD	Shit Flow Diagram
UN	United Nations
UNICEF	The United Nations Children's Fund
USSI	Urban Sanitation Status Index
WHO	World Health Organisation
RCC	Rajshahi City Corporation

1 INTRODUCTION

1.1 Research Background

Around 90% of faecal sludge is untreated in many cities (Peal et al., 2020) in Asia, Africa, and Latin America, which is a major source of faecal pollution (Berendes et al., 2017; Mills et al., 2018). The UN Sustainable Development Goal 6 (target 3) aims to improve water quality by halving the proportion of untreated wastewater by 2030 and a global survey identified this as a priority research area (Setty et al., 2020). Various assessment tools have been developed for the management of faecal matter within the sanitation service chain, such as the SFD (Shit Flow Diagram), SaniPath, CLUES (Community-Led Urban Environmental Sanitation) (Mtika & Tilley, 2020; Peal et al., 2014; Robb et al., 2017). The Shit Flow Diagram (SFD) is a widely used tool that provides a summary of the faecal management status of a whole city (Peal et al., 2014). However, the SFD and other tools cannot provide information on where the faecal waste is produced or where it is moving within the city at a spatial scale, which is essential for addressing the knowledge gap that exists in wastewater and faecal sludge management planning and decision-making. This is particularly important in unsewered urban catchments.

Globally, there are two main types of sanitation systems: sewered and unsewered. A sewer network is a network of pipes constructed principally for the purpose of conveying wastewater away from homes and businesses. Conventionally, the sewer network conveys wastewater to a wastewater treatment facility. These systems are predominantly found in developed countries. However, an unsewered urban catchment does not have such a network. It may have a network of open drains with the principal purpose of transporting rainwater runoff. On occasion, these are adapted to carry wastewater, and therefore acting like an informal open sewer.

Conventionally, pit latrines and septic tanks are designed to settle and/or store faecal sludge onsite. A pit latrine is a sanitation system that stores faecal solids in a below-ground pit, allowing liquid effluent to percolate into the surrounding

soil. It typically has no connection to a sewer or drain. Similarly, a septic tank is designed to settle and store faecal sludge within the tank prior to periodic removal, with the liquid effluent exiting through a pipe directed to a soak pit. By convention, a septic tank also has no connection to a sewer or drain.

In many cities in Asia, Africa, and Latin America, the combination of high rainfall, increasing populations, increasing water use, extensive use of pit latrines or septic tanks, high water table, and low soil permeability often leads to these sanitation systems overflowing. To prevent this overflow, residents sometimes informally connect their septic tanks and pit latrines to urban storm drains (Bari, 2017), creating a hybrid system. In this hybrid system, while the solids are contained onsite, the liquid fraction is transported to the drains to avoid overloading the soil (e.g., Otis & Sirotiak, 1987).

The design of septic tanks has evolved over time, but most septic tanks typically have two chambers, one of which is smaller. Faecal matter and wastewater go into the larger chamber, where they separate into solid and liquid waste. The liquid overflows into the smaller chamber and gets discharged into the soak pit through an outlet pipe (Tilley et al., 2014). However, in many cities septic tank outlet pipes are often not connected to a soak pit, and partially settled wastewater is directed to storm drains to transport the supernatant from the septic tanks and other liquid wastes in addition to rainwater within and out of the city (Foster et al., 2021; Tabassum, 2020). In many cases, septic tanks are not emptied on a regular basis. This neglect reduces their settling efficiency. As a result, a fraction of faecal solids overflows from the outlet pipe. These solids then travel throughout the city via drains. This leads to the accumulation of hazardous sludge in certain areas. Furthermore, this hazard becomes particularly concerning during extreme weather events, such as floods or heavy rains, as the overflowed sludge comes to the road, it amplifies the health risks involved. In these cities, urban hydrology is frequently governed by gravity-driven open channel flow (Li et al., 2020), and natural gradients are rarely ignored because of the risk of siltation and blockage. But there is little understanding of how faecal moves and where it concentrates.

The spatial understanding of sanitation infrastructure and faecal movement in cities is currently inadequate due to the challenging nature of conducting household-level surveys (the conventional means of data collection) with limited management systems and financial resources (Strande et al., 2018). However, free and open-source data present opportunities for various applications (Coetzee et al., 2020). These data can be used to improve spatial understanding and mapping capabilities for sanitation service chains. Then, urban hydrology can be used to study the movement of faecal matter both within and outside of cities by combining natural and engineered systems.

Bangladesh, for example, has implemented various management practices to address these sanitation challenges as part of its commitment to both the Millennium Development Goals and the Sustainable Development Goals (WaterAid, 2021). The nation has substantially decreased open defecation rates (now at 0% open defecation), primarily due to the extensive adoption of pit latrines, which are simple, covered holes in the ground for waste collection, and septic tanks, which are underground chambers that treat wastewater through settling and anaerobic processes (Strande et al., 2023). This trend is consistent across the country's 60 secondary cities. Secondary cities are urban areas that rank below the capital city of a country in terms of population and economic significance but play a critical role in regional economic systems (Marais & Cloete, 2017). These cities typically have populations between 0.5 and 3 million, where residents predominantly use septic tank facilities (Mansour & Esseku, 2017; WaterAid, 2021). However, irregular emptying of septic tanks leads to faecal overflow into drains, polluting watercourses and causing sludge accumulation in parts of the cities (Mehta et al., 2019; Tabassum, 2020). The situation is exacerbated by growing population density. In both low- and high-income areas within these cities, the direct discharge of untreated effluent into drains or the immediate environment is common practice (Mansour & Esseku, 2017). This urban sanitation scenario is reflective of secondary cities many of which have populations surpassing one million (Ezechiel & Baptiste Safari, 2020). Acknowledging the critical nature of this issue, recent research has advocated for

a comprehensive analysis of pathogen flows, particularly in densely populated regions (Alam et al., 2020; Amin et al., 2020; Foster et al., 2021).

The focus of this study is Rajshahi, a secondary city in northwest Bangladesh with a population of approximately 0.8 million. Rajshahi is generally considered a middle-class city in the context of Bangladesh (Walters, 2018). Economically, it is less affluent than Dhaka but plays a crucial role in the north-western part of the country, known for its silk industry, educational institutions, and agricultural contributions (BBS, 2013). Rajshahi, chosen to represent the features of a typical secondary city, provides a unique opportunity to develop and test a methodology for spatially demonstrating the sources and pathways of faecal matter. The knowledge gained from this study has substantial transferability potential for use in other secondary cities in Bangladesh as well as many cities in economically developing countries. This adaptability covers not just the research objectives, such as evaluating the uncertainty, but also the complexity of applying this technique to larger urban catchments.

In this context, the central research question guiding this study is: Can a spatial representation of sources, pathways and receptors of faecal sludge in urban catchments be used to create a new planning tool for pollution prevention using open-source data?

1.2 Aim and objectives

The aim is to generate a methodology for spatial scale understanding and representation of faecal matter sources, and its movement pathways in an unsewered urban catchment using open-source data. To deliver the aim, the following objectives were set:

- 1) To develop a prototype methodology for mapping faecal sources, pathways and the concentrated areas in a small sub-catchment
- 2) Addressing and assessing the uncertainty of the spatial pattern of faecal production and movement-
- 3) To identify and resolve the challenges of upscaling by applying the prototype methodology to a large urban catchment

A structured methodological approach was adopted to achieve the aim (Figure 1.1). This commenced with the development of a prototype model, to identify faecal sources, pathways, and receptors within a designated sub-catchment area, addressing the first objective. We termed this approach for characterising faecal sources, pathways, receptors, and their movement at a spatial scale as SanIFFlow (Sanitation Infrastructure and Faecal Flow). The prototype was followed by an uncertainty analysis to assess the model's accuracy and reliability, thus meeting the second objective. Field validation was then integrated to ensure the model's practical relevance, overcoming identified limitations.

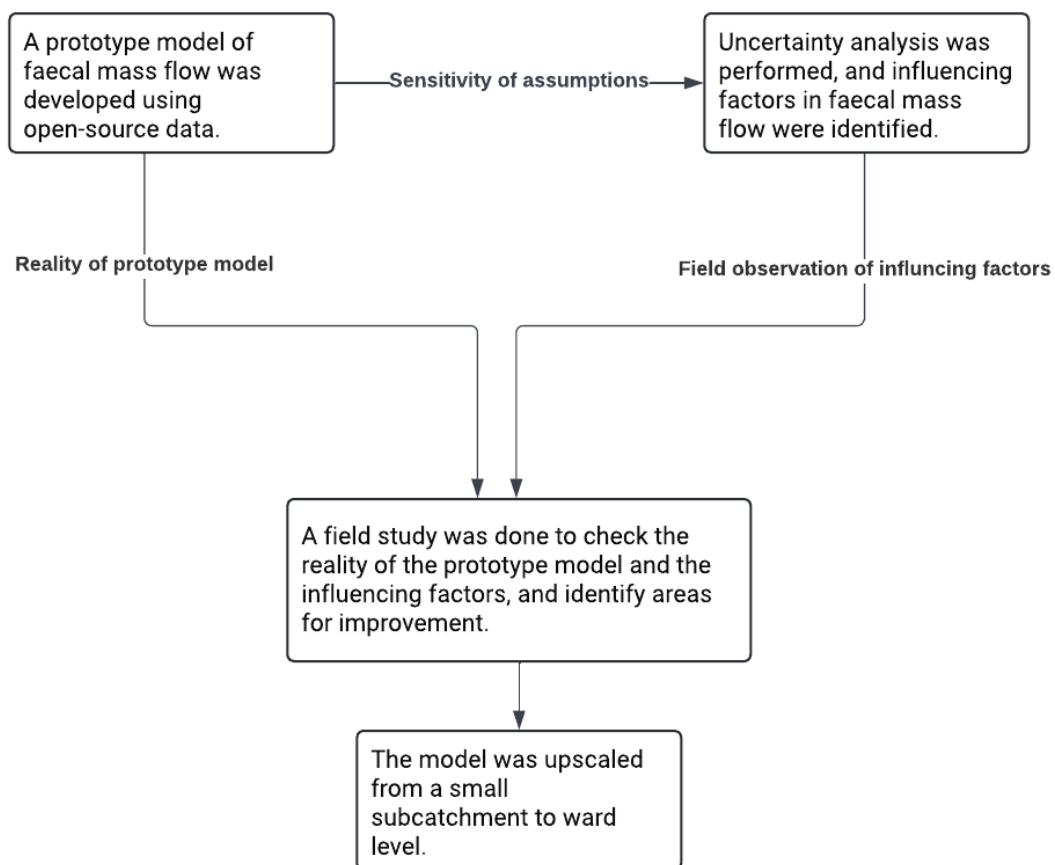


Figure 1.1: A flowchart that outlines the methodology for developing a spatial faecal mass flow model. It depicts the step-by-step process from creating a prototype using open-source data, through validation, to upscaling for broader urban applications. This demonstrates the model's practical utility and adaptability.

While household-level information such as the type of sanitation technology, faecal production rate, and the number of users is often unavailable, open-source data, such as remotely sensed elevation data, population density, and building footprint data, can be integrated to fill these gaps and provide valuable sanitation information for most cities.

Incorporating the SanIFFlow methodology, the final phase of this research entailed upscaling the approach to a larger urban catchment, demonstrating its adaptability and potential for broader applications in managing urban sanitation in unsewered cities. This systematic progression through the objectives not only enhanced the methodology but also fulfilled the overarching aim of the study by using open-source data to create a reliable and scalable tool for managing urban sanitation.

The aim and objectives of this study are strategically situated within the ongoing academic discourse and emerging research trends in faecal sludge management. This alignment with the current forefront of knowledge in the field is thoroughly explored in the subsequent section.

1.3 Current Perspectives and Research Needs

The history of faecal sludge management and drainage systems stretches back millennia, evolving alongside human civilization. Early practices in the Indus Valley and Ancient Rome laid the foundations with complex underground channels and innovative engineering (Strande et al., 2023). However, the medieval period saw a regression, often leading to the haphazard disposal of waste in streets and rivers. The Renaissance and industrial revolution brought incremental improvements, driven by urbanization and industrial needs. These eras witnessed the introduction of organised waste collection and the early stages of systematic waste treatment, setting the stage for future developments. Modern advancements, particularly from the mid-20th century onward, have focused on sophisticated treatment technologies that remove a variety of pollutants such as nitrogen compounds, phosphates, heavy metals like lead and mercury, and even in some cases organic contaminants like pesticides and pharmaceutical residues

(Qasem et al., 2021). Today, with an eye towards sustainability, wastewater management strategies are increasingly centred on energy efficiency, resource recovery, and decentralized solutions. These modern strategies are particularly vital in unsewered cities where challenges such as limited infrastructure and resource constraints necessitate innovative and adaptable solutions (Capodaglio et al., 2017). This historical journey, with its diverse stages from early innovations to modern sustainable practices, underlines the complexity and continuing evolution of systems that manage faecal pollution. The ongoing challenges in unsewered cities highlight the need for continued adaptation and innovation in this field.

1.3.1 An Interdisciplinary and Global Challenge

Effective sanitation management presents a complex and interdisciplinary challenge that requires coordinated global efforts and comprehensive strategies. According to UNICEF/WHO (2023), an estimated 4.2 billion people use sanitation services that leave human waste untreated. The Millennium Development Goals (MDG) advocated for improved access to toilets. The Sustainable Development Goals (SDG) extended this commitment by advocating an approach that takes into account the entire sanitation system as a means of achieving sustainable sanitation. The recent strategy developed by the World Bank and partners, including the Bill & Melinda Gates Foundation, following the SDG, Citywide Inclusive Sanitation (CWIS) initiative, aims to address the entire sanitation chain and ensure the inclusion of underserved neighbourhoods. CWIS promotes a range of solutions, both sewerred and unsewerred, tailored to the realities of urban areas. However, CWIS principles need to be integrated into national policies, technical standards, and utility management (Gambrill et al., 2020; Spuhler & Lüthi, 2020). Though this type of coordinated planning is rarely accomplished due to insufficient or narrowly allocated financing, lack of multi-stakeholder alignment, and limited technical capacities, there is also a lack of information on the spatial variation of sanitation coverage and conditions within cities. Currently, in most instances, management is fragmentary, often conducted in isolation using various assessment tools.

1.3.2 Methodological Innovations and evolutions in FSM

In the 21st century, the domain of Faecal Sludge Management (FSM) in low- and middle-income countries (LMICs) has advanced significantly, indicated by the development of diverse tools, methods and frameworks. The progress is evident across several critical areas such as: public health (Raj et al., 2020), environmental sustainability (Mtika & Tilley, 2020; Scott et al., 2015), urban planning and management (Peal et al., 2014), social and policy (Narayan et al., 2020; Willetts et al., 2020), geography and geospatial analysis (Hawkins & Muxímpua, 2015).

The assessment and management of sanitation often focus on understanding the health risks linked with faecal contamination. The SaniPath tool is instrumental in unveiling public health risks from faecal contamination, particularly in urban areas with lower incomes. Research by scholars like Robb et al. (2017), Mills et al. (2018), and Amin et al. (2020) have significantly contributed to the identification of key routes and sources of this contamination, including issues like contaminated street food and substandard septic tank management. While SaniPath effectively illustrates various exposure routes, it falls short of providing a complete picture of the movement of faecal matter in urban environments. This limitation restricts its ability to inform on the movement and management of faecal waste within the city's entirety, an aspect crucial for holistic faecal management planning. Furthermore, the tool's localised focus and immediate health risk assessment may overlook broader sustainability issues and systemic challenges in waste service management. The technical expertise and resources required for effective implementation of SaniPath present additional barriers, potentially hindering its adoption in resource-constrained environments where such a tool is most needed. Despite these challenges, SaniPath's deployment in cities and its use in informing local authorities for policy and programming demonstrate its utility (Raj et al., 2020). However, for comprehensive urban sanitation solutions, a tool that extends beyond individual exposure to encompass the entire faecal management lifecycle within the urban context is necessary.

1.3.3 Sanitation and environmental sustainability

Sanitation and environmental sustainability are closely intertwined in urban planning frameworks, particularly in the development and application of the Community-Led Urban Environmental Sanitation (CLUES) and Household-Centred Environmental Sanitation (HCES) approaches. CLUES, a progression from HCES, is a comprehensive guideline for planning and implementing environmental sanitation infrastructure and services, particularly in marginalised urban and peri-urban communities (Mtika & Tilley, 2020). It focuses on balancing the needs of people with environmental considerations, advocating for multi-sector and multi-actor involvement in the planning of water supply, sanitation, solid waste management, and storm drainage. This approach emphasizes broad community participation, extending beyond the household level, and is influenced by the lessons learned from the intensive piloting of HCES across various urban and peri-urban sites (Luthi et al., 2009). While CLUES is designed to complement citywide infrastructure planning approaches like the Sanitation 21 Framework or City Sanitation Plans, its application, as shown in pilot projects by Eawag, hinges on the presence of an enabling environment that includes political, legal, institutional, and socio-economic conditions (World Bank, 2003). Despite its comprehensive nature, CLUES, much like its predecessor HCES, may not fully address the need for a diagnostic tool capable of identifying sanitation issues across the entire service chain, particularly in terms of operational needs and political willingness. This gap underlines the necessity for additional, perhaps more streamlined, methodologies. For instance, the 'Sanitation Cityscape' developed by Scott et al. (2015) represents an innovative approach by integrating householders' investment logic with the fate of all faecal waste in a city. However, as Mills et al. (2018) indicated while conceptually valuable in visualising sanitation pathways, was limited to linear conceptual flow diagrams and did not employ quantitative measures. This limitation underscores the need for methodologies that not only provide a holistic view of the fate of faecal matter across the sanitation service chain but also incorporates quantitative aspects to enhance the understanding of sanitation challenges, particularly in unsewered urban environments.

1.3.4 Mapping of sanitation service chain

The early research on the spatial characterisation of faecal waste flows primarily depended on household surveys, as evidenced by a study conducted in 1993 in Kumasi, Ghana (Whittington et al., 1993). Utilising household survey data, this study provided valuable initial insights into the city's faecal waste generation and disposal practices. Although this offered useful information, the study's scope was limited and it encountered challenges similar to those outlined for the CWAS (2020) and Hawkins & Muxímpua (2015) studies, particularly regarding the extensive data coverage required.

Recent attempts have been made to spatially characterise the sanitation status of urban areas. A notable example is the Urban Sanitation Status Index (USSI), developed by Hawkins & Muxímpua (2015). This tool, which maps sanitation status, adapts the principles of the city-wide Shit Flow Diagram (SFD) to smaller neighbourhood scales, diverging from the traditional city-wide scope of SFDs. The USSI methodology primarily relies on field surveys at the household level and focus group discussions. While beneficial for identifying areas needing sanitation interventions, this approach is both expensive and time-consuming (Hawkins & Muxímpua, 2015). The extensive fieldwork and human resources required render the detailed sanitation mapping of an entire city using the USSI approach logistically challenging, if not prohibitive. Furthermore, the tool's inability to provide insights into the underlying reasons for inadequate service delivery, such as operational, institutional, or financial constraints, underscores the necessity of its use alongside other analytical tools. Consequently, while USSI represents an innovative step in applying SFD techniques to smaller areas, its practical application is limited by its resource-intensive nature.

Another tool that has emerged in the realm of sanitation mapping is SaniTab, an Android-based app initially developed for conducting sanitation surveys at the household level (CWAS, 2020). SaniTab stands out as a spatial tool, capable of generating baseline information for planning and monitoring Open Defecation Free (ODF) and Faecal Sludge Management (FSM) activities in urban settings. Its application extends to monitoring desludging operations, as seen in its use in

two cities in India. While SaniTab offers customization and potential efficiency, it is important to recognize its limitations. The tool's effectiveness largely depends on active household participation in the surveys. In scenarios where participation is low or inconsistent, the data quality and representativeness can be significantly compromised. Additionally, when surveyors are employed to collect data, the process can become expensive and time-consuming. This dependency on household engagement and the potential cost implications if conducted by surveyors are critical considerations in evaluating the practicality and scalability of SaniTab as a spatial sanitation mapping tool.

In 2014, Peal et al. advanced faecal waste flow mapping by creating a detailed diagram that quantifies the entire sanitation service chain, from containment to disposal or reuse (Peal et al., 2014). Their methodology utilises aggregated data from an entire city to differentiate between safe and unsafe practices, providing a clear visual representation of the system's bottlenecks. By 2020, their The Shit Flow Diagram (SFD) has gained widespread acceptance for its capacity to simplify data into a format that policymakers can easily understand (Peal et al., 2020). Its strength lies in the succinct, single-image summary that conveys essential information to a broad audience, regardless of their technical background. The minimal data requirements for generating an SFD make it a versatile tool in diverse settings and a powerful instrument for advocacy and decision support, easily interpreted by stakeholders and the wider community. It can direct the focus towards more effective and inclusive urban sanitation solutions. The success of the SFD is attributed to its simplification of intricate sanitation management ideas, promoting informed decisions and policy-making. Nevertheless, the utility of an SFD hinges on the data quality it embodies. In places where data reliability is an issue, it may lead to inaccurate interpretations. Additionally, while SFDs offer valuable snapshots, they are less equipped to convey the spatial complexities within urban areas.

1.3.5 The Role of Open-Source Data

Open-source data, freely available for use, modification, and distribution, plays an important role in research across various fields. For instance, NASA's open

data on climate and earth sciences have been instrumental in environmental research. The open-source data facilitates innovative problem-solving, collaboration, and educational opportunities, making research more accessible and transparent. In recent years, a variety of free and open-source datasets, such as those from OpenStreetMap Contributors (2019) and LandScan's population data (Rose et al., 2020), have become available. These resources have been applied in diverse areas, including a methodology developed by Vu et al. (2021) for producing urban functional land use maps. Such developments underscore the growing importance and versatility of open-source data in contemporary research.

However, the application of open-source data in sanitation practices is currently underutilised. There is promise that this data can help identify sources of faecal production, their movement pathways, and capture the spatial attributes of sanitation status in unsewered cities. The availability of open-source data can enrich spatial understanding and may offer potential solutions for a pressing issue: estimating faecal production at a spatial scale, which is essential for designing effective management and treatment solutions. Strande et al. (2018) proposed a method to reliably estimate the total accumulated quantities and qualities (q & q method) of faecal sludge, an empirical approach applied in Kampala, Uganda through sampling diverse sources. The main challenge in applying this approach on a city-wide scale, however, lies in the laborious and costly nature of the required survey. By utilising geo-referenced population data and other open-source datasets, like OpenStreetMap building data and elevation data, researchers could potentially develop more scalable and plausible methods for estimating the volume and production of faecal matter at a city-scale level (Leyk et al., 2019). This approach would address one of the critical gaps in current methodologies and pave the way for more effective sanitation management strategies.

1.3.6 Faecal flow model and hydrological aspects of a city

The challenges in managing faecal sludge are well-recognised, there remains a significant gap in the literature regarding the spatial understanding of faecal

movement within urban areas. A key aspect that has often been overlooked is the incorporation of urban hydrology to explore the dynamics of faecal flow. The research conducted by Li et al. (2020) and Salvatore et al. (2015) demonstrates the potential of this approach. The integration of hydrological information into FSM may provide a significant advancement. However, the application of open-source elevation data in this context remains largely underutilised, warrants further exploration to fully harness its potential in improving FSM strategies.

Open drains for urban storm water management are prevalent in many low- and middle-income regimes, like South Asia, Sub-Saharan Africa, and Latin America. (Barbosa et al., 2012). These drainage systems, which blend natural and engineered channels, are primarily shaped by the land's topography. However, they present significant public health risks as they often carry untreated wastewater, acting as conduits for both wastewater and faecal matter towards the outskirts of the city (Bari et al., 2018; Foster et al., 2021; Mills et al., 2018).

In many secondary cities, faecal matter management is usually done via septic tanks. However, these tanks often lack connections to soak pits because the shallow water table, which leads to the channelling of partially treated wastewater into open drains (Bari & Kabir, 2023; Opel et al., 2012; Peal et al., 2020). This situation exacerbates environmental pollution and heightens public health risks.

Furthermore, irregular septic tank emptying leads to overflowing faecal matter in the drain, which builds up sludge and eventually reaches the street, especially during severe weather events like floods (Mehta et al., 2019; Sultana et al., 2023; Tabassum, 2020). In Bangladesh, where nearly one-third of urban residents lack access to safely managed sanitation (Amin et al., 2020), have emphasised the importance of understanding pathogen flows from on-site sanitation systems, especially in densely populated urban areas (Alam et al., 2020; Amin et al., 2020; Foster et al., 2021).

1.3.7 Current trend and Research Needs

Achieving safe and sustainable urban sanitation remains a crucial goal for cities. Current sanitation management tools (Kaupp, 2016), while adept within their

specific domains, often fall short when it comes to holistic and cost-effective urban sanitation management, particularly in the rapidly expanding and complex unsewered urban areas (Peal et al., 2020). Because these are not designed to identify problem spatially which can allow maintenance and resource prioritisation. Existing models, such as SFD, identify sanitation issues for an entire city, while others like SaniPath focus on specific areas. However, these models lack spatial assessment because they are static and unconnected to the system, failing to account for the movement of waste within the interconnected system. Also, the limitations of existing tools, which include extensive time requirements for spatial data gathering, and often not integrated to local level policy, underline the need for an innovative approach. A spatially adept tool, developed by open-source data, such as the proposed SanIFFlow (Sanitation Infrastructure and Faecal Flow) tool, could address this gap. This tool would integrate the detailed diagnostics, monitoring capabilities, and advocacy efforts currently provided separately by tools like SaniPath (Raj et al., 2020), USSI (Hawkins & Muxímpua, 2015), and SaniTab (CWAS, 2020). Additionally, it would enhance the individual strengths of existing frameworks such as SFD, CLUES, and CWIS to offer a more integrated solution.

Establishing the SanIFFlow model could potentially address key challenges by developing clear metrics through robust data collection and monitoring systems that incorporate spatial data, allowing for accurate tracking of sanitation service outcomes and impacts, and enabling precise identification of areas with the greatest need. Additionally, the model could help redesign financing mechanisms using spatial data to pinpoint cost-effective intervention points and optimise resource allocation. By integrating sanitation principles into policies and regulations, spatial analysis could inform urban planning and governance frameworks, explicitly addressing sanitation needs in specific locations.

Thus, the integration intended in the fishbone diagram i.e. cause-and-effect diagram (Tague, 2005) points towards a new generation of tools composed to unite these diverse functions, facilitating the development of safe and sustainable urban environments (Figure 1.2). The diagram selectively emphasizes tools,

those related to the spatial aspects of sanitation. For a more detailed description of various available tools, readers can refer to Kaupp (2016).

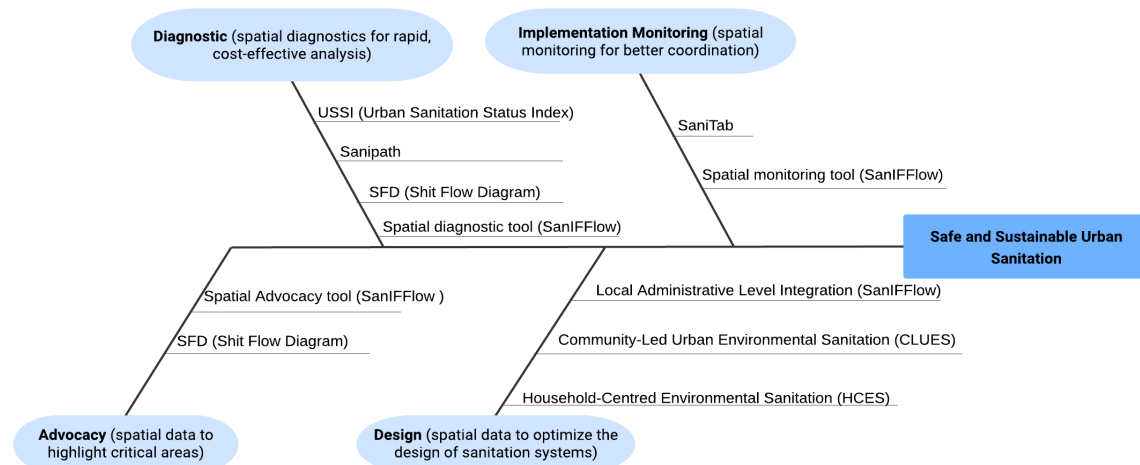


Figure 1.2: Integrating Sanitation Management Tools - This fishbone diagram illustrates the interplay between existing tools and highlights the need for SanIFlow, a proposed tool focused on spatial aspects. SanIFlow aims to integrate diagnostics, monitoring, and advocacy within the existing service delivery framework, enhancing the design and implementation of safe and sustainable urban sanitation systems.

SanIFlow addresses urban sanitation management challenges by utilising open-source data such as remote sensing data, LandScan gridded population data at 1 km resolution (Bustos et al., 2020), OSM building data (OpenStreetMap Contributors., 2019), and ALOS PALSAR 12.5 m digital elevation model data (ASF DAAC, 2015). Unlike other frameworks, SanIFlow does not require specific household-level sanitation data, such as the quality of septic tanks or sludge conditions, for its initial application. Instead, it provides an initial status assessment of faecal sludge management using open-source data. However, for more detailed and upscaled applications, additional data such as records from city authorities on the frequency of septic tank emptying, identification of buildings without toilets, and distinctions between residential and commercial toilets will be necessary.

The SanIFFlow approach is specifically designed to improve sanitation management in cities that rely on septic tanks and manage wastewater through storm drainage systems. It utilizes spatial and infrastructural data to model faecal production and its flow paths, providing a more comprehensive understanding of urban sanitation dynamics. This approach is crucial for addressing the existing gaps in sanitation management practices. While SanIFFlow provides a novel framework for spatial understanding and developing a methodology for faecal generation and movement pathways in urban environments, its applicability is constrained by local sanitation infrastructure. In cities where pit latrines are the predominant form of sanitation containment, or where storm drainage systems are absent, the utility of SanIFFlow is limited as that will then only characterize the spatial variations of faecal production but not the movement.

1.4 Chapter summary encompassing how the knowledge gap was addressed

The thesis is structured in a paper format. Chapters 2 to 5 consist of four papers, while Chapter 1 serves as an introduction, offering a brief review of the relevant literature and identifying research needs. This section also includes a summary of the thesis structure (Table 1.1), and outlining how the thesis addresses some of these research needs, providing an overview with detailed information in each subsequent chapter. Chapter 6 encompasses the overall discussion and conclusion, showcasing the contributions to knowledge made by this research.

All papers are authored by M. Sufia Sultana (MS), Dr.Toby Waine (TW), Professor. Niamul Bari (NB), and Professor. Sean Tyrrel (ST). The study was designed by MS under the guidance of ST and TW. MS executed the work, drafted the initial manuscript in consultation with ST and TW, and refined it through several iterations based on their comments and feedback. The final drafts were reviewed by ST, TW, and NB. NB contributed local data and participated in discussions to contextualize various findings, providing verbal feedback. Chapter 2 has been published in the Journal of Water, Sanitation and Hygiene for Development (2023), 13(4): 289–300 and others are in the process of submission to journals for consideration.

Table 1.1: Thesis chapters according to chapters and thesis objectives.

Chapter number	Chapter title	Thesis objectives	Paper number	Publication status
1	Introduction	-		
2	Towards a new spatial representation of faecal sources and pathways in unsewered urban catchments using open-source data	1	1	Published
3	An analysis of factors that influence the spatial pattern of faecal matter flow in unsewered cities.	2	2	In Preparation (Abstract is published in a conference proceeding)
4	Assessing the reliability and utility of open-source data used for spatial scale characterisation of urban sanitation infrastructure- a field study in Rajshahi, Bangladesh	2	3	In Preparation (Presented at a conference)
5	City-Scale Spatial Mapping Of Faecal Production And Movement In Unsewered Urban Areas: SanIFFlow – An Integrated Planning And Management Tool	3	4	In Preparation (Presented at a conference)
6	Over all discussion and conclusion	-		

1.4.1 Chapter 2

This chapter presents the prototype methodology for spatial modelling of urban sanitation systems using open-source data. Combining building footprint, population and elevation data along with cities drainage data, a novel approach is demonstrated to map faecal sources, pathways and loads in an unsewered catchment of Rajshahi, Bangladesh. This addresses the knowledge gap around lack of geospatial sanitation data by pioneering the application of open-source spatial data. However, uncertainties are highlighted around representing influencing factors on faecal flows.

1.4.2 Chapter 3

Building on the methodology from Chapter 2 this chapter addressed an uncertainty analysis to interrogate the prototype model assumptions. Testing sensitivity to alternative assumptions reveals how minor factors can collectively and significantly alter model outcomes when integrated spatially. This addresses the knowledge gap around understanding complexity and uncertainties in sanitation systems. Key insights are generated around spatial dynamics of influencing factors as critical for robust modelling.

1.4.3 Chapter 4

A fieldwork was carried out to assess the model's assumptions and collect data on influencing factors (Chapter 2). Findings provide qualitative confirmation of the methodology's reliability in representing broader sanitation infrastructure and flows. However, the need for empirical data to capture finer management details like septic tank emptying is underlined. The fieldwork addresses the building level approach is not yet suitable for practical implementation as the city authority does not any framework for maintaining their services in that level however, they have a framework for administrative and other purposes in ward level. For the effective sanitation management purposes that ward level scale may play an important role. Therefore, in chapter 5 an up-scaled model is developed.

1.4.4 Chapter 5

This chapter develops an up scaled ward-level model aligned with municipal boundaries to identify an appropriate spatial scale for practical planning. However, uncertainties around loss of heterogeneity through spatial aggregation are noted. This addresses the knowledge gap around optimal spatial scales for sanitation planning. Further work is highlighted as needed to incorporate empirical monitoring data.

1.4.5 Chapter 6

Over all discussion and conclusion. The chapter synthesises new findings to meet set objectives and delineate contributions to knowledge. It demonstrates how a geospatial modelling approach aids in understanding sanitation in unsewered cities through low-cost, open-source data mapping.

References

- Alam, M.-U., Sharior, F., Ferdous, S., Ahsan, A., Ahmed, T., Afrin, A., Sarker, S., Akand, F., Archie, R. J., Hasan, K., Renouf, R., Drabble, S., Norman, G., Rahman, M., & Tidwell, J. B. (2020). Strategies to Connect Low-Income Communities with the Proposed Sewerage Network of the Dhaka Sanitation Improvement Project, Bangladesh: A Qualitative Assessment of the Perspectives of Stakeholders. *International Journal of Environmental Research and Public Health*, 17(19), 7201. <https://doi.org/10.3390/ijerph17197201>
- Amin, N., Liu, P., Foster, T., Rahman, M., Miah, M. R., Ahmed, G. B., Kabir, M., Raj, S., Moe, C. L., & Willetts, J. (2020). Pathogen flows from on-site sanitation systems in low-income urban neighborhoods, Dhaka: A quantitative environmental assessment. *International Journal of Hygiene and Environmental Health*, 230, 113619. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113619>
- ASF DAAC. (2015). *ALOS PALSAR Radiometric Terrain Corrected high*

- resolution*. The ASF (Alaska Satellite Facility) Distributed Active Archive Center (DAAC). <https://doi.org/10.5067/Z97HFCNKR6VA>
- Barbosa, A. E., Fernandes, J. N., & David, L. M. (2012). Key issues for sustainable urban stormwater management. *Water Research*, 46(20), 6787–6798. <https://doi.org/10.1016/j.watres.2012.05.029>
- Bari, M. N. (2017). Study on Existing Faecal Sludge Management Situation in Rajshahi Rajshahi City. *Proceedings of the WasteSafe 2017 – 5th International Conference on Solid Waste Management in South Asian Countries 25-27 February 2017, Khulna, Bangladesh STUDY*, March.
- Bari, M. N., & Kabir, M. R. (2023). *Urban Sanitation Facilities and Its Management in Rajshahi City Urban Sanitation Facilities and Its Management in Rajshahi City*. November.
- Bari, N., Bushra, A., & Zaman, J. (2018). Management of faecal sludge by rajshahi city corporation. *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development*, July, 1–11. http://www.iccesd.com/proc_2018/Papers/r_p4803.pdf
- BBS. (2005). *Statistical Yearbook of Bangladesh*. Bangladesh Bureau of Statistics.
- BBS. (2013). *Rajshahi District Statistics 2011* (Issue June).
- Berendes, D. M., Sumner, T. A., & Brown, J. M. (2017). Safely Managed Sanitation for All Means Fecal Sludge Management for At Least 1.8 Billion People in Low and Middle Income Countries. *Environmental Science & Technology*, 51(5), 3074–3083. <https://doi.org/10.1021/acs.est.6b06019>
- Blackett, I., Hawkins, P., & Heymans, C. (2014). *The Missing Link in Sanitation Service Delivery: A Review of Fecal Sludge Management in 12 Cities*. <https://doi.org/10.13140/RG.2.1.4072.7205>
- Bustos, M. F. A., Hall, O., Niedomysl, T., & Ernstson, U. (2020). A pixel level evaluation of five multitemporal global gridded population datasets: a case

- study in Sweden, 1990–2015. *Population and Environment*, 42(2), 255–277.
<https://doi.org/10.1007/s11111-020-00360-8>
- Capodaglio, A. G., Callegari, A., Cecconet, D., & Molognoni, D. (2017). Sustainability of decentralized wastewater treatment technologies. *Water Practice and Technology*, 12(2), 463–477.
<https://doi.org/10.2166/wpt.2017.055>
- Clemett, A., Amin, M., & Ara, S. (2006). *Background Information for Rajshahi City, Bangladesh*.
- Coetzee, S., Ivánová, I., Mitsova, H., & Brovelli, M. A. (2020). Open Geospatial Software and Data: A Review of the Current State and A Perspective into the Future. *ISPRS International Journal of Geo-Information*, 9(2).
<https://doi.org/10.3390/ijgi9020090>
- CWAS. (2020). *Using Sani Tab for monitoring scheduled emptying operations in two cities in Maharashtra – Wai and Sinnar*.
https://pas.org.in/Portal/document/UrbanSanitation/uploads/sanitab_slide_deck_part_2_9dec.pdf
- Deng, Z., Huang, D., He, Q., & Chassagne, C. (2022). Review of the action of organic matter on mineral sediment flocculation. *Frontiers in Earth Science*, 10. <https://doi.org/10.3389/feart.2022.965919>
- Dissanayake, Amin, M. M., Amerasinghe, P., & Clemett, A. (2007). Baseline Water Quality Survey for Rajshahi, Bangladesh. In *WASPA Asia: Project Report 7*.
- Ekklesia, E., Shanahan, P., Chua, L. H. C., & Eikaas, H. S. (2015). Temporal variation of faecal indicator bacteria in tropical urban storm drains. *Water Research*, 68, 171–181.
<https://doi.org/https://doi.org/10.1016/j.watres.2014.09.049>
- Englund, M., Carbajal, J. P., Ferré, A., Bassan, M., Hoai Vu, A. T., Nguyen, V.-A., & Strande, L. (2020). Modelling quantities and qualities (Q&Q) of faecal sludge in Hanoi, Vietnam and Kampala, Uganda for improved management

- solutions. *Journal of Environmental Management*, 261, 110202. <https://doi.org/https://doi.org/10.1016/j.jenvman.2020.110202>
- ESRI. (2019). *Understanding the Utility Network: A Guide for Water Utilities*. <https://www.esri.com/en-us/landing-page/industry/water/2019/understanding-utility-network>
- Ezechiel, N., & Baptiste Safari, J. (2020). Assessing the Impact of Secondary City Development on Sanitation Services: The Case of Muhanga District 2013-2017. *International Journal of Natural Resource Ecology and Management*, 5(3), 90. <https://doi.org/10.11648/j.ijnrem.20200503.12>
- Fisher, P. (1997). The pixel: A snare and a delusion. *International Journal of Remote Sensing*, 18(3), 679–685. <https://doi.org/10.1080/014311697219015>
- Foster, T., Falletta, J., Amin, N., Rahman, M., Liu, P., Raj, S., Mills, F., Petterson, S., Norman, G., Moe, C., & Willetts, J. (2021). Modelling faecal pathogen flows and health risks in urban Bangladesh: Implications for sanitation decision making. *International Journal of Hygiene and Environmental Health*, 233, 113669. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113669>
- Gambrill, M., Gilsdorf, R. J., & Kotwal, N. (2020). Citywide Inclusive Sanitation—Business as Unusual: Shifting the Paradigm by Shifting Minds. *Frontiers in Environmental Science*, 7(February), 1–10. <https://doi.org/10.3389/fenvs.2019.00201>
- Gil, J., Beirão, J. N., Montenegro, N., & Duarte, J. P. (2012). On the discovery of urban typologies: Data mining the many dimensions of urban form. *Urban Morphology*, 16(1), 27–40. <https://doi.org/10.51347/jum.v16i1.3966>
- Google. (n.d.). *Google Earth Pro v.7.3.4.8248 (64-bit)*. Retrieved January 17, 2021, from [kh.google.com](https://www.kh.google.com)
- Greger, K. (2015). Spatio-temporal building population estimation for highly urbanized areas using GIS. *Transactions in GIS*, 19(1), 129–150. <https://doi.org/10.1111/tgis.12086>

- Hawkins, P., & Muxímpua, O. (2015). Developing Business Models for Fecal Sludge Management in Maputo. In *Water and Sanitation Program* (Issue June). <https://wsp.org/sites/wsp.org/files/publications/WSP-Developing-Business-Models-for-Fecal-Sludge-Management-Maputo.pdf>
- HBRI. (2015). *Bangladesh National Building Code*.
- Hyun, C., Burt, Z., Crider, Y., Nelson, K. L., Prasad, C. S. S., Rayasam, S. D. G., Tarpeh, W., & Ray, I. (2019). Sanitation for Low-Income Regions: A Cross-Disciplinary Review. *Annual Review of Environment and Resources*, 44(1), 287–318. <https://doi.org/10.1146/annurev-environ-101718-033327>
- IRC. (2017). *Faecal Waste Flow Calculator*. <https://www.ircwash.org/tools/faecal-waste-flow-calculator>
- Islam, M. S., Islam, S. M., & Islam, A. M. (2021). Assessment of efficacy of drainage system in Rajshahi City Corporation, Bangladesh. *Advances in Environmental Research*, 10(2), 105–116. <https://doi.org/10.12989/aer.2021.10.2.105>
- Jenks, G. F. (1977). Optimal data classification for choropleth maps. *Department of Geography, University of Kansas Occasional Paper*.
- Jenson, S. K., & Domingue, J. O. (1988). Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing*, 54(11), 1593–1600.
- Kaupp, R. (2016). *Comparison of tools & approaches for urban sanitation September 2016 Introduction*. <https://policycommons.net/artifacts/2333103/comparison-of-tools-approaches-for-urban-sanitation-september-2016-introduction/3093766/>
- Kelkar, V., & Seetha Ram, K. (2019). a Literature Review Evaluating New Approaches To Resolving the Sanitation Challenge in Developing Asia. In *ADB Working Paper Series* (Issue 976). <https://www.adb.org/publications/evaluating->

- Koné, D. (2010). Making urban excreta and wastewater management contribute to cities' economic development: a paradigm shift. *Water Policy*, 12(4), 602–610. <https://doi.org/10.2166/wp.2010.122>
- Leidig, M., Teeuw, R. M., & Gibson, A. D. (2016). Data poverty: A global evaluation for 2009 to 2013 - implications for sustainable development and disaster risk reduction. *International Journal of Applied Earth Observation and Geoinformation*, 50, 1–9. <https://doi.org/https://doi.org/10.1016/j.jag.2016.03.001>
- Leong, W. K., Ngo, A. L. K., Wong, A. C. H., Ling, J. H., & Sia, H. T. (2022). The Mandatory 4 Years Desludging Frequency of Underground Septic Tanks in Residential Areas: A Case Study in Sibu Sarawak, East Malaysia. *Journal of the Civil Engineering Forum*, 8(2 SE-Articles). <https://doi.org/10.22146/jcef.3812>
- Leyk, S., Gaughan, A. E., Adamo, S. B., de Sherbinin, A., Balk, D., Freire, S., Rose, A., Stevens, F. R., Blankespoor, B., Frye, C., Comenetz, J., Sorichetta, A., MacManus, K., Pistolessi, L., Levy, M., Tatem, A. J., & Pesaresi, M. (2019). The spatial allocation of population: a review of large-scale gridded population data products and their fitness for use. *Earth System Science Data*, 11(3), 1385–1409. <https://doi.org/10.5194/essd-11-1385-2019>
- Li, C., Fan, Z., Wu, Z., Dai, Z., Liu, L., & Zhang, C. (2020). Methodology of sub-catchment division considering land uses and flow directions. *ISPRS International Journal of Geo-Information*, 9(11). <https://doi.org/10.3390/ijgi9110634>
- Luthi, C., Morel, A., Kohler, P., & Tilley, E. (2009). *People's Choice First: A 4-Country Comparative Validation of the HCES Planning Approach for Environmental Sanitation*.
- Lüthi, C., Willetts, J., & Hoffmann, S. (2020). Editorial: City-Wide Sanitation: The Urban Sustainability Challenge. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.585418>

- Mansour, G., & Esseku, H. (2017). Situation analysis of the urban sanitation sector in Ghana. *WSUP - Water & Sanitation for the Urban Poor*, July, 27.
- Marais, L., & Cloete, J. (2017). The role of secondary cities in managing urbanisation in South Africa. *Development Southern Africa*, 34(2), 182–195. <https://doi.org/10.1080/0376835X.2016.1259993>
- Mehta, M., Mehta, D., & Yadav, U. (2019). Citywide Inclusive Sanitation Through Scheduled Desludging Services: Emerging Experience From India. *Frontiers in Environmental Science*, 7. <https://doi.org/10.3389/fenvs.2019.00188>
- Mills, F., Willetts, J., Petterson, S., Mitchell, C., & Norman, G. (2018). Faecal pathogen flows and their public health risks in urban environments: A proposed approach to inform sanitation planning. *International Journal of Environmental Research and Public Health*, 15(2). <https://doi.org/10.3390/ijerph15020181>
- Mtika, W. M., & Tilley, E. (2020). Environmental Sanitation Planning: Feasibility of the CLUES Framework in a Malawian Small Town. *Frontiers in Environmental Science*, 7. <https://doi.org/10.3389/fenvs.2019.00204>
- Müller, A., Österlund, H., Marsalek, J., & Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. *Science of The Total Environment*, 709, 136125. <https://doi.org/10.1016/j.scitotenv.2019.136125>
- Narayan, A. S., Fischer, M., & Lüthi, C. (2020). Social Network Analysis for Water, Sanitation, and Hygiene (WASH): Application in Governance of Decentralized Wastewater Treatment in India Using a Novel Validation Methodology. *Frontiers in Environmental Science*, 7(January). <https://doi.org/10.3389/fenvs.2019.00198>
- Niwagaba, C. B., Mbéguéré, M., & Strande, L. (2014). Faecal Sludge Quantification, Characterisation and Treatment Objectives. In L. Strande, M. Ronteltap, & D. Brdjanovic (Eds.), *Faecal Sludge Management Systems Approach for Implementation and Operation* (pp. 19–44). IWA Publishing.

- Opel, A., Bashar, M. K., & Ahmed, M. F. (2012). Faecal sludge management in Bangladesh : an issue that needs urgent attention. *Asia Regional Sanitation and Hygiene Prtitioners Workshop, February*, 1–9.
- OpenStreetMap Contributors. (2019). *Planet.osm*.
<https://planet.openstreetmap.org/>
- Otis, R. J., & Sirotiak, K. (1987). Sewer-Septic Tank Hybrid Promises Savings. *Civil Engineering*, 57, 74–76.
<https://api.semanticscholar.org/CorpusID:114298165>
- Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Services Research*, 34(5 Pt 2), 1189.
- Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., Schoebitz, L., Scott, R., Sleigh, A., Strande, L., & Veses, O. (2020). Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned From a Global Implementation of Excreta-Flow Diagrams. *Frontiers in Environmental Science*, 8, 1. <https://doi.org/10.3389/fenvs.2020.00001>
- Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2014). Fecal sludge management (FSM): analytical tools for assessing FSM in cities. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 371–383.
<https://doi.org/10.2166/washdev.2014.139>
- Qasem, N. A. A., Mohammed, R. H., & Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: a comprehensive and critical review. *Npj Clean Water*, 4(1). <https://doi.org/10.1038/s41545-021-00127-0>
- Quang, C. N. X., Giang, N. N. H., Hoa, H. V., & Hung, P. Q. (2022). Effects of sediment deposit on the hydraulic performance of the urban stormwater drainage system. *IOP Conference Series: Earth and Environmental Science*, 964(1), 12020. <https://doi.org/10.1088/1755-1315/964/1/012020>
- Rahaman, M. F., Ali, M. S., Arefin, R., Mazumder, Q. H., Majumder, R. K., & Jahan, C. S. (2020). Assessment of drinking water quality characteristics and quality index of Rajshahi city, Bangladesh. *Environment, Development and*

Sustainability, 22(5), 3957–3971. <https://doi.org/10.1007/s10668-019-00366-9>

Raj, S. J., Wang, Y., Yakubu, H., Robb, K., Siesel, C., Green, J., Kirby, A., Mairinger, W., Michiel, J., Null, C., Perez, E., Roguski, K., & Moe, C. L. (2020). The SaniPath Exposure Assessment Tool: A quantitative approach for assessing exposure to fecal contamination through multiple pathways in low resource urban settlements. *PLoS ONE*, 15(6), 1–18. <https://doi.org/10.1371/journal.pone.0234364>

Rasul, M. T., & Jahan, M. S. (2010). Quality of Ground and Surface Water of Rajshahi City Area for Sustainable Drinking Water Source. *Journal of Scientific Research*, 2(3), 577. <https://doi.org/10.3329/jsr.v2i3.4093>

Robb, K., Null, C., Teunis, P., Yakubu, H., Armah, G., & Moe, C. L. (2017). Assessment of fecal exposure pathways in low-income urban neighborhoods in Accra, Ghana: rationale, design, methods, and key findings of the Sanipath study. *American Journal of Tropical Medicine and Hygiene*, 97(4), 1020–1032. <https://doi.org/10.4269/ajtmh.16-0508>

Rodriguez, F., Le Delliou, A.-L., Andrieu, H., & Gironás, J. (2020). Groundwater Contribution to Sewer Network Baseflow in an Urban Catchment-Case Study of Pin Sec Catchment, Nantes, France. In *Water* (Vol. 12, Issue 3). <https://doi.org/10.3390/w12030689>

Roldin, M., Fryd, O., Jeppesen, J., Mark, O., Binning, P. J., Mikkelsen, P. S., & Jensen, M. B. (2012). Modelling the impact of soakaway retrofits on combined sewage overflows in a 3km² urban catchment in Copenhagen, Denmark. *Journal of Hydrology*, 452–453, 64–75. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2012.05.027>

Rose, A. N., McKee, J. J., Sims, K. M., Bright, E. A., Reith, A. E., & Urban, M. L. (2020). *LandScan 2019* (2019 RI-). Oak Ridge National Laboratory SE - July 1, 2020. <https://landscan.ornl.gov/>

Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The Characterization

- of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Critical Reviews in Environmental Science and Technology*, 45(17), 1827–1879. <https://doi.org/10.1080/10643389.2014.1000761>
- RWASA. (2022). *Yearly Report 2021-2022 (Bengali)*. http://rajshahiwasal.portal.gov.bd/sites/default/files/files/rajshahiwasal.portal.gov.bd/page/475e362d_7060_4662_9fc4_ce5da8acf69c/2022-10-16-04-40-a2a51c26c52a31be0cc2a9c3cd19ae76.pdf
- Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Espeland, W., Kay, J., Lo Piano, S., Mayo, D., Jr, R., Portaluri, T., Porter, T., Puy, A., Rafols, I., Ravetz, J., Reinert, E., Sarewitz, D., Stark, P., & Vineis, P. (2020). Five ways to ensure that models serve society: a manifesto. *Nature*, 582, 482–484. <https://doi.org/10.1038/d41586-020-01812-9>
- Salvadore, E., Bronders, J., & Batelaan, O. (2015). Hydrological modelling of urbanized catchments: A review and future directions. *Journal of Hydrology*, 529, 62–81. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2015.06.028>
- Schmidt, M. (2008). The Sankey Diagram in Energy and Material Flow Management. *Journal of Industrial Ecology*, 12(2), 173–185. <https://doi.org/https://doi.org/10.1111/j.1530-9290.2008.00015.x>
- Schrecongost, A., Pedi, D., Rosenboom, J. W., Shrestha, R., & Ban, R. (2020). Citywide Inclusive Sanitation: A Public Service Approach for Reaching the Urban Sanitation SDGs. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00019>
- Scott, P., & Cotton, A. P. (2020). The Sanitation Cityscape – Toward a Conceptual Framework for Integrated and Citywide Urban Sanitation. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00070>
- Scott, P., Cotton, A., & Sohail, M. (2015). Using tenure to build a “sanitation cityscape”: narrowing decisions for targeted sanitation interventions.

Environment and Urbanization, 27(2), 389–406.
<https://doi.org/10.1177/0956247815569415>

- Sercu, B., Van De Werfhorst, L. C., Murray, J. L. S., & Holden, P. A. (2011). Sewage Exfiltration As a Source of Storm Drain Contamination during Dry Weather in Urban Watersheds. *Environmental Science & Technology*, 45(17), 7151–7157. <https://doi.org/10.1021/es200981k>
- Setty, K., Jiménez, A., Willetts, J., Leifels, M., & Bartram, J. (2020). Global water, sanitation and hygiene research priorities and learning challenges under Sustainable Development Goal 6. *Development Policy Review*, 38(1), 64–84. <https://doi.org/https://doi.org/10.1111/dpr.12475>
- Shawky, M., Moussa, A., Hassan, Q. K., & El-Sheimy, N. (2019). Pixel-Based Geometric Assessment of Channel Networks/Orders Derived from Global Spaceborne Digital Elevation Models. *Remote Sensing*, 11(3). <https://doi.org/10.3390/rs11030235>
- Spuhler, D., & Lüthi, C. (2020). Review of frameworks and tools for urban strategic sanitation planning: considering technology innovations and sustainability. *Journal of Water, Sanitation and Hygiene for Development*, 10(4), 768–785. <https://doi.org/10.2166/washdev.2020.062>
- Strahler, A. (1952). Dynamic Basis of Geomorphology. *GSA Bulletin*, 63(9), 923–938. [https://doi.org/10.1130/0016-7606\(1952\)63\[923:DBOG\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1952)63[923:DBOG]2.0.CO;2)
- Strande, L., Evans, B., von Sperling, M., Bartram, J., Harada, H., Nakagiri, A., & Nguyen, V.-A. (2023). Urban Sanitation: New Terminology for Globally Relevant Solutions? *Environmental Science & Technology*, 0(0), null. <https://doi.org/10.1021/acs.est.3c04431>
- Strande, L., Ronteltap, M., & Brdjanovic, D. (2014). *Faecal Sludge Management – Systems Approach for Implementation and Operation*. IWA Publishing. <https://doi.org/10.2166/9781780404738>
- Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B. J., & Niwagaba, C. B. (2018). Methods to reliably estimate faecal sludge

- quantities and qualities for the design of treatment technologies and management solutions. *Journal of Environmental Management*, 223(June), 898–907. <https://doi.org/10.1016/j.jenvman.2018.06.100>
- Strande, L., Velkushanova, K., & Brdjanovic, D. (2021). Setting the stage. In B. D. and B. C. Velkushanova K., Strande L., Ronteltap M., Koottatep T. (Ed.), *Methods for Faecal Sludge Analysis* (pp. 1–14). IWA Publishing.
- Sultana, M. S., Waine, T., Bari, N., & Tyrrel, S. (2023). Towards a new spatial representation of faecal sources and pathways in unsewered urban catchments using open-source data. *Journal of Water, Sanitation and Hygiene for Development*, 13(4), 289–300. <https://doi.org/10.2166/washdev.2023.227>
- Tabassum, S. (2020). Drainage system, its water quality and health effect: A case study of Rajshahi city, Bangladesh. *Scientific Journal of Environmental Sciences*, 9(1), 323–336. <https://doi.org/10.14196/sjes.v9i1.2612>
- Tague, N. R. (2005). *The Quality Toolbox* (2nd ed.). ASQ Quality Press.
- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P., Schertenleib, R., & Zurbrugg, C. (2014). *Compendium of Sanitation Systems and Technologies* (2nd Revise). Swiss Federal Institute of Aquatic Science and Technology (Eawag).
- UNICEF/WHO. (2023). *Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender*. United Nations Children’s Fund (UNICEF) and World Health Organization (WHO). https://washdata.org/sites/default/files/2022-01/jmp-2021-wash-households_3.pdf
- Vandenbulcke, L., & Barth, A. (2019). Upscaling of a local model into a larger-scale model. *Ocean Science*, 15(2), 291–305. <https://doi.org/10.5194/os-15-291-2019>
- Vu, T. T., Vu, N. V. A., Phung, H. P., & Nguyen, L. D. (2021). Enhanced urban functional land use map with free and open-source data. *International Journal of Digital Earth*, 14(11), 1744–1757.

<https://doi.org/10.1080/17538947.2021.1970262>

- Walters, P. (2018). The limits to participation: Urban poverty and community driven development in Rajshahi City, Bangladesh. *Community Development*, 49(5), 539–555. <https://doi.org/10.1080/15575330.2018.1537296>
- WaterAid. (2018). *SFD Lite Report of Rajshahi City Corporation Bangladesh*.
- WaterAid. (2021). *WaterAid, Bangladesh and SDG 6. September*, 1–9. <https://www.wateraid.org/bd/wateraid-bangladesh-everyone-everywhere-by-2030>
- Whittington, D., Lauria, D. T., Choe, K., Hughes, J. A., Swarna, V., & Wright, A. M. (1993). Household sanitation in Kumasi, Ghana: A description of current practices, attitudes, and perceptions. *World Development*, 21(5), 733–748. [https://doi.org/10.1016/0305-750X\(93\)90030-D](https://doi.org/10.1016/0305-750X(93)90030-D)
- Willettts, J., Mills, F., & Al'Afghani, M. (2020). Sustaining Community-Scale Sanitation Services: Co-management by Local Government and Low-Income Communities in Indonesia. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00098>
- Woolley, S. M., Buckley, C. A., Pocock, J., & Foutch, G. L. (2014). Rheological modelling of fresh human faeces. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 484–489. <https://doi.org/10.2166/washdev.2014.088>
- World Bank. (2003). *Enabling Environments for Civic Engagement in PRSP Countries*. <http://hdl.handle.net/10986/11319>
- Zeng, C., Wang, J., Zhan, W., Shi, P., & Gambles, A. (2014). An elevation difference model for building height extraction from stereo-image-derived DSMs. *International Journal of Remote Sensing*, 35. <https://doi.org/10.1080/01431161.2014.975375>

2 TOWARDS A NEW SPATIAL REPRESENTATION OF FAECAL SOURCES AND PATHWAYS IN UNSEWERED URBAN CATCHMENTS USING OPEN- SOURCE DATA¹

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2.1 Highlights

- This is a first known attempt to map sanitation infrastructure at a spatial scale in unsewered urban catchments by utilising widely available open-source data.
- A prototype method for creating a spatial representation of faecal sources and movement has been developed.
- It shows how utilisation of open-source data can be combined to create a map for sanitation management planning, where in situ data is rare.

2.2 Abstract

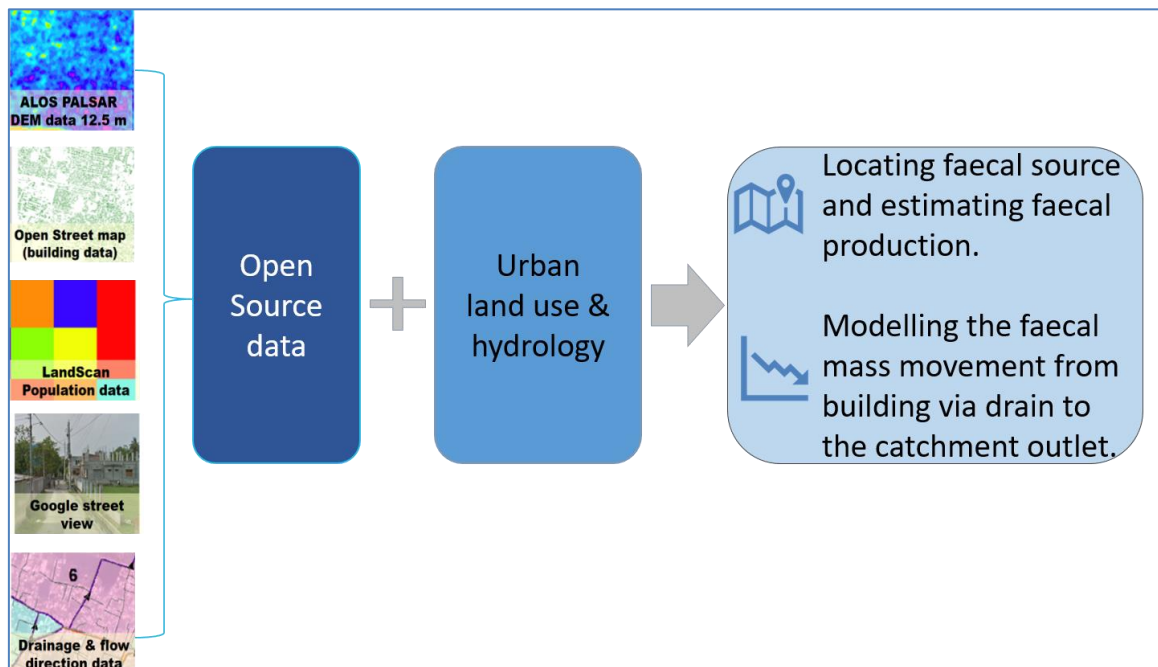
Spatial representation of sanitation infrastructure and service coverage is essential for management planning and prioritising services. The provision of sanitation services is inherently unequal because the sanitation infrastructure is

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lacking, and on-site sanitation is managed individually. Here we developed a prototype method for creating a spatial representation of faecal sources and movement in a small area in Rajshahi city in northwest Bangladesh, which is representative of 60 other such secondary cities. We demonstrate an approach to estimate spatial variability in faecal production at the building scale by combining widely accessible building, ground elevation, and population data. We also demonstrate an approach to attribute potential faecal movement pathways by integrating drainage data (only data collected from Rajshahi City Corporation, RCC), and faecal production at the building scale. We made use of free and open-source data and provide answers to the broader topic of spatial representation of faecal mobility in unsewered urban settings.

Key words: Open-source data, Bangladesh, Rajshahi, faecal movement, spatial representation, unsewered, urban catchment

2.3 Graphical Abstract



2.4 Introduction

In many urban areas over 90% of faecal sludge is left untreated (Peal et al., 2020), which is a major contributor to faecal pollution (Mills et al., 2018). Faecal waste ends up in local drains and waterbodies due to the inconsistent sanitation service chain and a lack of sewer infrastructure. Furthermore, septic tanks are not regularly emptied, resulting in a large fraction of faecal overflows into drains (Tabassum, 2020), resulting in pollution of watercourses and sludge accumulation in some parts of the city, which may be hazardous, and this hazard reinforces the health consequences when extreme weather occurs, such as floods.

In order to improve the situation, UN SDG6 intends to enhance sanitation services while halving the proportion of untreated wastewater by 2030 (Setty et al., 2020). Sanitation service chain models that portray the components of faecal sludge management (FSM) as a linear process, i.e., the capture, storage, transport, treatment, and reuse/disposal of faecal waste, have significantly advanced the unsewered sanitation services in the most recent decade (IRC, 2017). For example, the widely used SFD method (excreta flow diagram), is a great tool for advocacy and awareness-raising and can provide us with information about the sanitation status of the entire city (Peal et al., 2014). According to an SFD lite report of Rajshahi city in Bangladesh (WaterAid, 2018), only 10% of faecal matter is safely contained and we don't know what happens to the remaining 90%, particularly in terms of spatial characteristics. Because of the paucity of data, present methods are still unable to provide spatial information on how much faecal matter is produced, where and how it is moving, as well as the areas where the faecal matter may concentrate or where individuals are more likely to be exposed to it.

Faecal waste is mostly maintained at the individual household level and on an informal basis in these cities, through the use of septic tanks and pits. Septic tanks are often constructed underground, with two chambers, one of which is two-thirds the size of the tank. An inlet pipe transports the faecal matter and flushed water to the bigger chamber, where it is held to separate the liquid and solid

waste, allowing supernatant fluid to overflow into the second, smaller chamber, from where it is discharged into the drains via the outlet pipe (Tilley et al., 2014). In theory, the majority of the faecal solids should be stored in the tank awaiting emptying and offsite disposal. In practice, a lack of emptying means that faecal solids probably exit the tank to the drain once the tank is full. These drains are therefore carrying all the wastewater throughout the city (Foster et al., 2021). The mapping of sanitary infrastructure, including faecal movement in cities, is a data-intensive procedure that necessitates a household-level survey, which is a massive effort due to inadequate management systems, financial resources, and technical competence (Strande et al., 2018). For this reason, spatial understanding and mapping capabilities for the sanitation service chain are limited. However, over the last decade, several free and open datasets (OpenStreetMap Contributors., 2019), and Landsat population data (Rose et al., 2020) have emerged, allowing them to be used in a variety of applications (Coetzee et al., 2020), for example, a methodology to produce urban functional land use map (Vu et al., 2021).

The current use of open-source data in sanitation practices is limited. So, the research focuses on how to spatially represent urban sanitation in where in situ data is rarely available, with a special emphasis on faecal production sources, faecal movement pathways, and areas where they concentrate using open-source data. To address the aim of the work, Rajshahi, a city in northwest Bangladesh that is representative of 60 other secondary cities around the country, has been chosen as an example.

2.5 Description of the study area

Rajshahi is a metropolitan city, and one of the major urban, commercial and educational centres of Bangladesh. Located on the north bank of the Padma River, near the Bangladesh-India border, the city consists of 30 wards with a total area of ~90 km² and a home to around 0.8 million people (WaterAid, 2018).

The climate of the city is generally marked by monsoons, high temperature, considerable humidity and a mean annual rainfall of ~1500 mm compared to a national average of 2500 mm (BBS, 2005). The surface geology consists mainly

of sedimentary formations, mostly riverine in origin. The area has a general slope from south to north with a ground elevation of 17.0-18.0 m Public Works Datum (PWD - ± 0.5 m to sea level) in (Figure 2.1). Although the city is situated on the left bank of the Ganges River (locally known as the Padma) because of the northward slope, the area is drained by a local river called the Baranai – a tributary of Brahmaputra (Dissanayake et al., 2007).

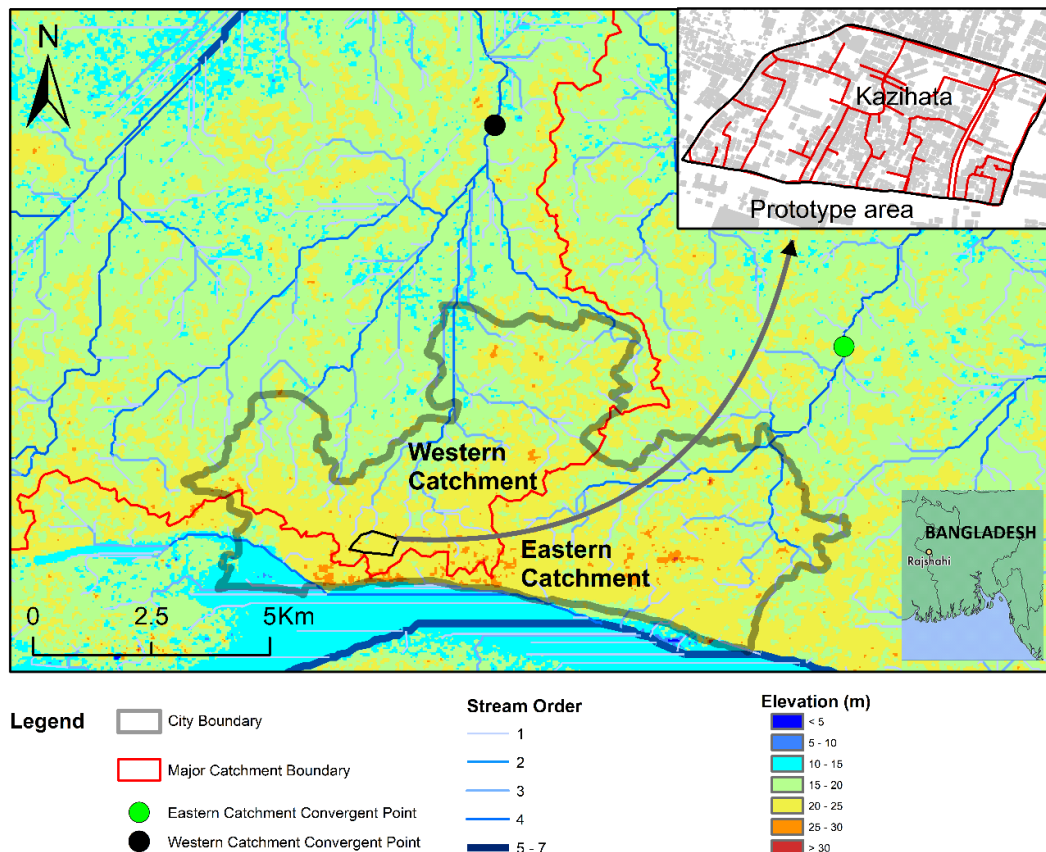


Figure 2.1: Rajshahi city and its catchments along with the prototype area. The city is mostly divided into two catchments: eastern and western. Each of these catchments is composed of several sub-catchments. The prototype area is one of the mini-catchment in a sub-catchment. Streams are classified according to the Strahler stream order² (Strahler, 1952).

²Strahler stream order: a hierarchical numbering system for streams based on the structure of their tributaries. In this system, the smallest unbranched tributaries are assigned an order of 1. When two streams of the same order converge, the resulting stream is assigned the next higher order.

Water and Sanitation: The water supply coverage in the city has improved greatly in recent years (Rahaman et al., 2020; Rasul & Jahan, 2010). The Rajshahi Water Supply and Sewerage Authority (RWASA) was established in 2010, and is currently providing clean water to 84% of the population. Nearly 80% of the supplies come from groundwater with 110 production wells connected to a pipe network and rest is surface water based (RWASA, 2022). The remainder of the population is supplied by individually maintained tube wells.

The city has no sewerage network therefore, people essentially use onsite sanitation where the majority uses septic tanks (80%) with largely cistern-flush system and the rest rely on toilets connected to pits (WaterAid, 2018). However, two-thirds of the septic tanks are connected to an open drain. Only 10% follow the Bangladesh National Building Code (BNBC) specifications of soak pits to avoid discharge to open water courses (Bari et al., 2018; Tabassum, 2020; WaterAid, 2018). A number of storm water drains – which are in fact converted natural drains - flow from the south through the city to the north and either merge in beels (cropland) or the Baranai River, some 15 km away (Dissanayake et al., 2007). Most of the pit latrines are managed with no outlet but the base is open to the ground allowing fluid to seep and occasionally if there is an overflow, it may drain into the natural drainage system (WaterAid, 2018).

There is one 2000-litre portable vacuum tanker (vacutug) that is used for collecting and transporting faecal sludge from septic tanks to the designated informal dumping site in the northern outskirts, as there is no treatment plant in place (Bari, 2017). The uses of the vacutug are limited, since it only emptied one septic tank when it first started in 2011 and since has grown in popularity, resulting in the emptying of 30 septic tanks per year as of June 2017 (Bari, 2017; Bari et al., 2018).

2.6 Data and method

A prototype area of 0.31 km² was chosen conveniently to create the methodology of spatial representation of faecal production sources and pathways. The

availability of the Google Street View data was a consideration for choosing the area. The area was considered to be a representative sample of larger areas as it has similar buildings patterns, such as multi-story residential and commercial buildings, and storm drainage characteristics. This could also generate reliable results that could be generalised to other areas. This sub-catchment has around 900 buildings and most of those are residential multi-storey and home to around 9000 people. The buildings which are located by the major roads have mixed use with commercial activities restricted to the ground floors with few exceptions where the entire building is commercial or used as a public facility (e.g., schools, hospitals). The area is heavily built-up with a few constructed ponds and open spaces.

It has its own catchment with some local drains and each drain has its own service households. As a result, the spatial representation can provide information on estimated faecal output at each building as well as faecal mass flow in local drains.

We have been utilising faecal mass as a faecal movement indicator in the model. In addition, access to Google Street View data has been emphasized to investigate the drainage.

2.6.1 Data

The study has taken the opportunity of using Open source LandScan gridded population data at 1 km resolution representing an ambient population (average over 24 hours) distribution (Bustos et al., 2020) combining with available OSM building data (OpenStreetMap Contributors., 2019) along with ALOS PALSAR 12 m digital elevation model data which allowed to estimate faecal production at the building level. The DEM data was downloaded from the Alaska Satellite Facility Distributed Active Archive Data Center (ASF DAAC, 2015) in geographic information systems (GIS)-ready GeoTIFF format with a horizontal resolution of 12.5 m. This data has the most vertical accuracy than any other DEM available (Shawky et al., 2019).

2.6.2 Methods

The method consisted of a model which has two connected sub-models: (i) Population distribution and faecal production in each building and (ii) Building to drain connectivity and Sankey representation of faecal movement in drains (Figure 2.2). Model inputs comprised a combination of estimates based on relevant scientific literature as well as space data collected and analysed from various sources as explained below. Around nine hundred households have been included in the model to predict their expected effect on faecal production and spatial representation of the area. The model also identified the challenges and uncertainties of different scenarios relating to the spatial scale, city's land use and current sanitation management practices.

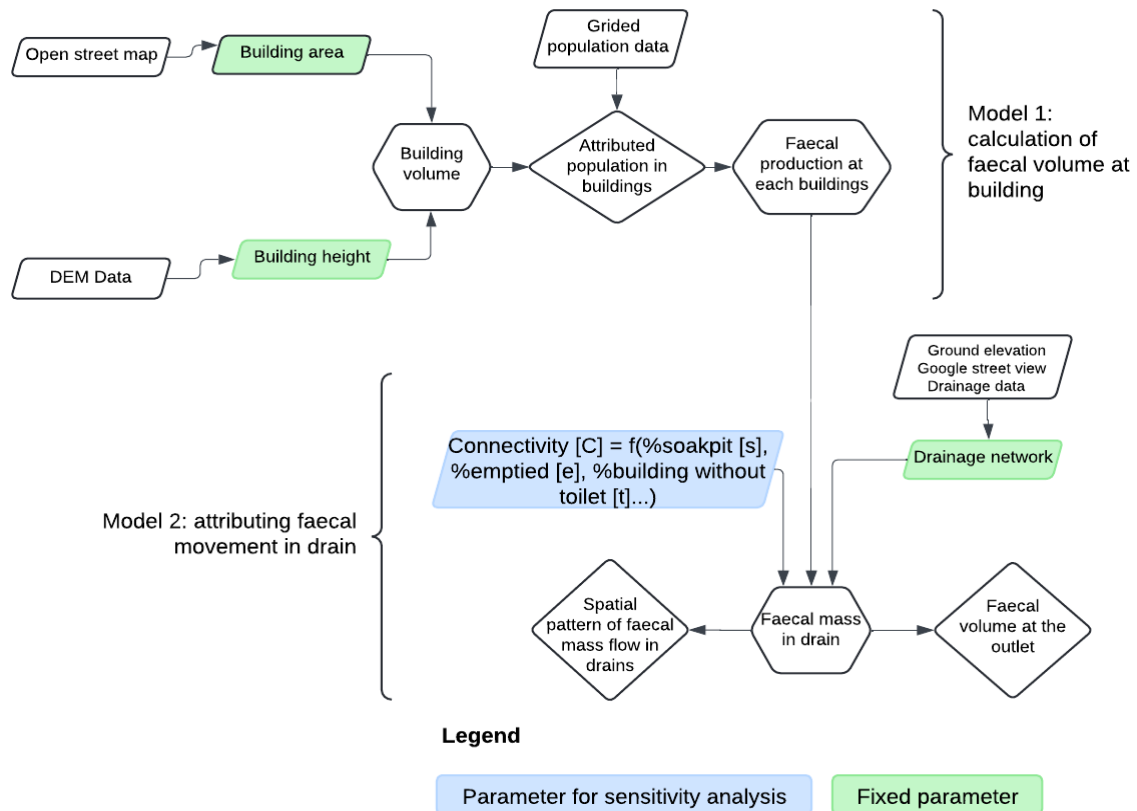


Figure 2.2: Major input parameters in two stages modelling of the faecal movement analysis. The symbols used in the flowchart are conventionally applied: the parallelogram represents data collection, the hexagon indicates preparation steps involving data processing, and the diamond signifies decision points based on the prepared data.

(i) Population distribution and faecal production in each building

Open street map for building information along with Google Earth image and Google Street View (Google, n.d.) have been used to locate the buildings which are assumed to possess septic tanks. The faecal volume for a building was determined by distributing the gridded population (Rose et al., 2020) to buildings in a GIS framework using the dasymetric method, which relies on quantitative areal ancillary data on the building height and footprint to relocate population (Leyk et al., 2019). Individuals only reside in buildings where faecal production happens, therefore gridded population data is transformed to gridded population per building to exclude open areas, and the link between building volume and building population produces faecal production data.

The building height was calculated by using DEM data which has two steps: 1) the top of the building was chosen by the highest values of the building polygon. The highest value of the elevation within each building polygon has been extracted rather than a constant highest value because the building polygon itself may shift due to digitisation error and mixed pixel effects (Zeng et al., 2014) which are common at the edges of the buildings. 2) The ground elevation was retrieved from adjacent areas of the buildings. To do that a buffer area with 100 m (~8 pixels of DEM data in each direction) from the building polygon boundary was created which included the building and adjacent areas with other buildings and open spaces. The minimum elevation within the buffer polygon has been mined in a view to find the base elevation. The minimum value (inside the buffer polygon) will be less affected by mixed-pixel effect and will more correctly represent the spatial variability of ground elevation.

The building height was then computed by subtracting the minimum value from the maximum value. Finally, the volume of each building was calculated by multiplying its area by its height (Zeng et al., 2014).

Once we had the total volume of buildings in a population grid, we divided the total population by the total volume of buildings to get the population per volume of buildings.

Then the population at each building was calculated by multiplying the population per building volume by the volume of each building. The faecal mass at each building is then determined by multiplying the population number by 250 g/d per capita faecal (wet) mass, as the previous study found 128 g/cap/day moist faecal mass in developed countries, but it can be double in developing countries due to fibre-rich dietary intake (Niwagaba et al., 2014; Rose et al., 2015), and then converted to annual faecal mass by multiplying by 365 days.

(ii) Building to drain connectivity and Sankey representation of faecal movement

The integrated hydrological analysis of natural and engineered drains in relation to faecal movement has been conceptualised taking into account of the hydrological flow and flow direction of engineered drains. There is no information available on the pathways between households and drains but often these are service pipes connected to the nearest drain (Foster et al., 2021). The centroid (assumed location of septic tank) of each building has been connected using proximity analysis i.e., the shortest distance to the nearest drain by a line in a GIS environment.

A drainage network map with household connection paths of the prototype catchment has been prepared. The flow directions of each channel have been identified with the help of natural slope analysis (Jenson & Domingue, 1988), flow direction of major engineered drains and checking with Google Street view data where available.

The building centre (septic tank) locations are used as sources, while the catchment outlet (receptor) is used as a sink (ESRI, 2019). The prototype area has only one sink, which is the catchment's outlet, as determined by the flow direction and the lowest elevated point within the area. The utility network analysis generates the flow direction using basic sources and sinks rules. The potential faecal mass conveyed by each drain has been determined using this

network. The amount of faecal solids ending up in the drains from individual septic tanks is subject to various factors including the presence of soak pit, prior emptying, and a building that may not have a toilet in the first place. However, in this case, it was assumed that all produced faecal solids ended up in drains and were considered as an indicator of faecal movement. The flow variation in this connected drain network is demonstrated by relating the width of the lines to its flow rate in units of ton/yr using the Sankey concept (Schmidt, 2008), and therefore, the diagrams reveal where the focus of mass flow is occurring. A Jenks natural break classification system is used to show the variability as this gives the most optimal class range found "naturally" in a data set and it seeks to minimize the average deviation from the class mean while maximizing the deviation from the means of the other groups (Jenks, 1977).

2.7 Results

2.7.1 Buildings and Population distribution pattern

The prototype area is mostly covered by one major population grid and intersects with two additional grids. This part of the city is densely populated, with about 20,000 people living in a square kilometre and the estimated population of the prototype area is around 9000.

The area is a highly built-up place with a variety of building sizes and a greater number of 3 to 5-storied buildings. Buildings occupied about 40% of the overall area, with a mix of residential and commercial uses, while roads, open space, and ponds took up the remainder. There is a secondary school, a hospital, a bank, and a few other businesses in the area.

When the size of the building is considered, the majority of buildings are less than 200 m², with little variation in building sizes with respect to the area. When height is taken into consideration, however, there is noticeable spatial variability, with taller buildings in the prototype area's centre (Figure 2.3).

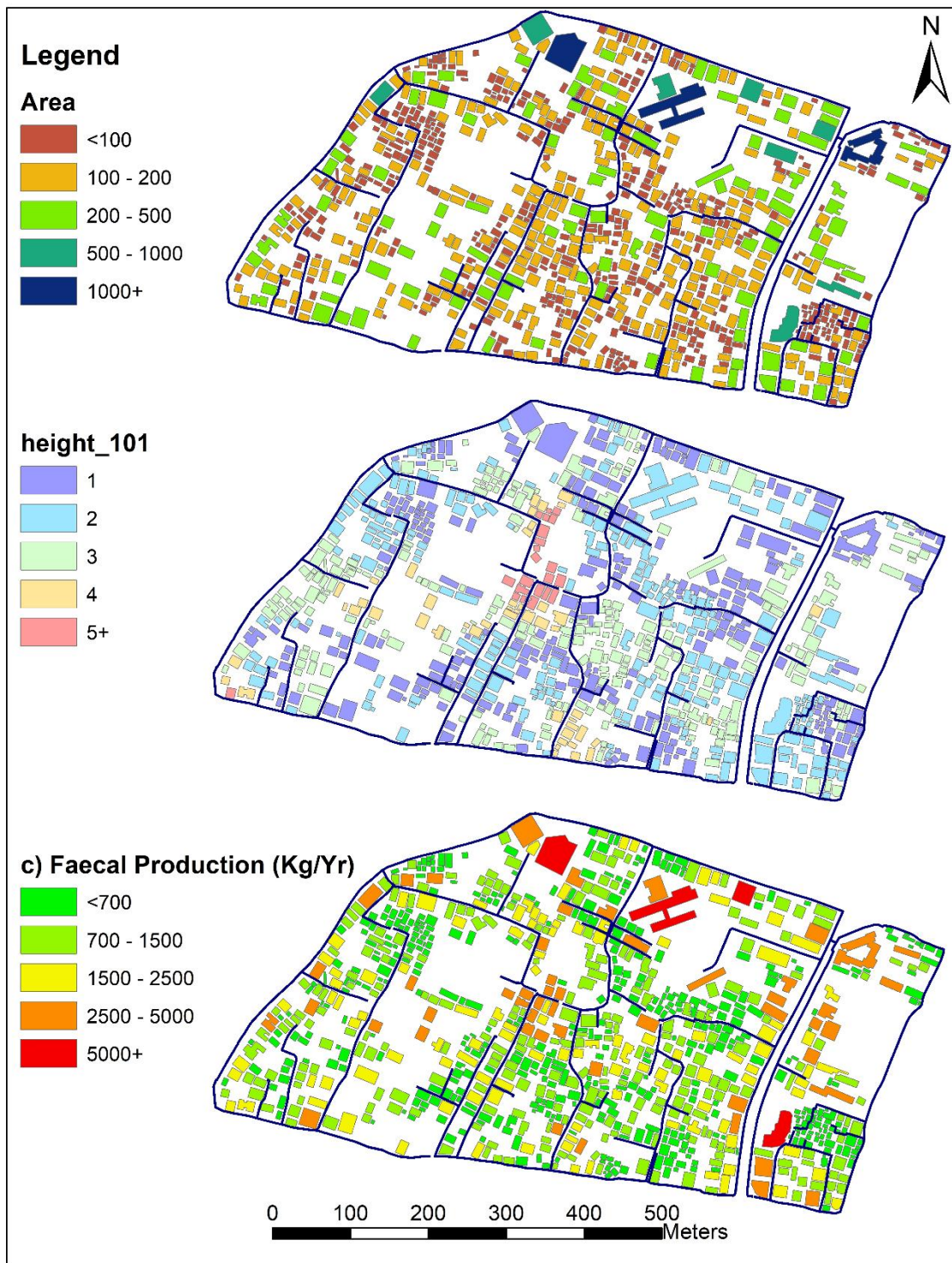


Figure 2.3: Spatial variation of building height (a), area (b), and faecal mass production at each building (c) across the prototype catchment. The distribution of large buildings with faecal mass >5000 kg/yr is uneven.

2.7.2 Faecal production at buildings and their pattern

The data reveal that faecal output varies widely between buildings (Figure 2.3). In the area, buildings with higher storeys or a greater footprint create more faecal matter as a result of the model assumption that population is directly correlated to building volume. The spatial variation within the prototype area is explained by the height and size of the buildings. Majority of the high faecal producing buildings are located in the centre of the area which are mostly high-rise buildings while buildings with larger foot print have faecal production over 5000 kg/yr. Most of the buildings in the area produced faecal <1500 kg/yr.

2.7.3 Faecal movement and Sankey representation

The Sankey representation shows the faecal mass flow pattern inside the area, where there are three service catchments, with the middle one having higher faecal mass flow due to being more densely populated than the other two (Figure 2.4). The thinner lines show less faecal mass, whereas the wider lines show more. The inner small lines also represent its width depending on the proportion of faecal mass.

2.8 Discussion

2.8.1 Identifying the sources of faecal production and spatial representation:

We all know that the source of faecal matter is the population (Englund et al., 2020; Strande et al., 2018), however, positioning the population, where the faecal produces, and how it will relate to faecal movement pathways is technically challenging, particularly in unsewered environments (Foster et al., 2021; Mills et al., 2018). This study used building data from an open street map to locate the sources where the building centroid was assumed to be a faecal production location. Normally, existing methods of estimating faecal production (Peal et al., 2020; Strande et al., 2018) take the population and estimate faecal production based on the total population for the entire city. The limitation of this method is that we are unable to determine the places with the highest concentrations of faecal matter, as well as the magnitude of spatial variability. Collecting data at the

household level is too labour intensive, especially in areas where there is no existing information (Peal et al., 2014; Strande et al., 2018). There is no proven method that exists which can quantify faecal production in urban areas (Strande et al., 2018). In order to obtain a good spatial estimate of faecal production, the number of users and the location are important parameters (Peal et al., 2014; Strande et al., 2018) which we show is possible to estimate using remotely sensed data. However, in this preliminary approach, people were allocated evenly throughout buildings based on their volume, which was a pragmatic arbitrary assumption for the purposes of building a prototype and which will need to be improved in future versions of the model.

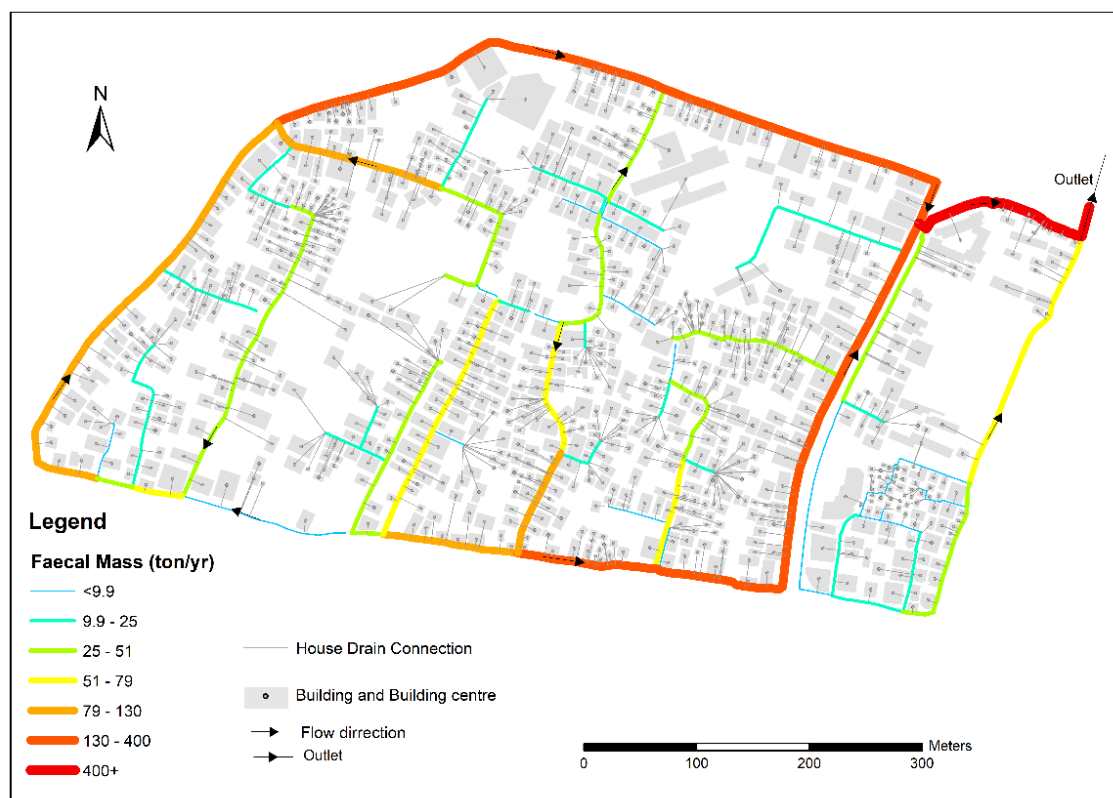


Figure 2.4: Sankey representation of faecal movement. The discharge point i.e., outlet of the catchment is located in the top of the northeast corner which is carrying 810 tonnes of faecal mass on a yearly basis. The values were categorised using Jenks natural breaks (with two significant digits rounding) as mentioned in the method section.

The centre of the plot was taken as the location of the septic tank. The actual location is unknown since the specific location is not set conventionally, some are on the front side of the house, others are on the backside, and some are on one of the sides of the house (Bari, 2017). However, the septic tanks are located within the plot since the plot holder would need to construct the tank within their property rather than outside. As a result, this is a consistent and arbitrary method of allocating a spatial location in the GIS representation. Another question that may arise from this representation is that faecal matter is produced at all buildings irrespective of their types, e.g., residential, commercial or part residential part commercial buildings. By using open-source data, it is beyond the scope at this method to know about the land use at building level, for example: which building is occupied, or which one is partly used for commercial purposes. Therefore, it is assumed that the uses of non-household toilets are equally important to include when evaluating faecal production. In low-income countries as the large number of people who go into urban areas on a regular basis would use those toilets in commercial buildings. Estimating faecal production at each building is easy mathematically since the number of people in each building is multiplied by waste produced per day per person. The problem is that the population at each building based on satellite data was not error-free, and person per day faecal output is affected by a variety of factors. People are assigned to buildings based on building volume, which is computed based on the building's height and area (Zeng et al., 2014). Previous studies have found that the volumetric technique is better for attributing people in cities than the area metric method, which is better for rural regions (Greger, 2015). Building heights retrieved from satellite data are consistently lower than their real heights due to mixed pixel effects, which are common in cities (Fisher, 1997). However, as building volume was used as a ratio to relocate population from the gridded area to the buildings it will have less influence and may be an interim solution until we find a better way of estimating the building heights from satellite data or other means.

We used an average of 250 g per person per day faecal matter production (Rose et al., 2015) in our estimation of faecal production. In reality, there is likely to be significant variability around this mean in the amount of faecal production which

vary between family members (age and gender) and between families because of food habit. In a building there are around 8 to 10 families, and the faecal production will vary between the individuals. As here we are estimating faecal volume at building level the individual variability may be incorporated within the average we took. Therefore, there is a limited possibility of a significant effect in the faecal production estimation.

2.8.2 Identification of faecal movement pathways:

Open drains, which are a mix of engineered and natural channels that follow ground slopes, carry wastewater and overflowed faecal matter from sources to the outskirts of the city (Bari et al., 2018). Our model depicts the faecal mass flow pathways via the drain network and spatial variability all the way to the catchment outlet. The model considered the source and sink attributes to demonstrate the representation of flow-paths. Determination of the flow-paths were subject to two types of connection issues: one was establishing the connection from building to drain and other one was drain to drain connection. There is no data available on the pathways between households and drains but often these are connected by service pipes and open drains are identified a key pathway for faecal pathogens (Amin et al., 2020; Foster et al., 2021). Here we assumed this to be nearest drain where that is connected. This may be true in the majority of cases, however if a building is located at the intersection of two drains, the house could be connected to any one of those irrespective of their distances. Influence of such buildings on faecal flow structure may be very small given this is not the situation with many buildings. Despite the fact that the engineered channels in these cities are natural channels that have been modified to fit the purpose and managed, they mostly follow the natural gradients and flow paths to minimise sedimentation and clogging. To establish the drain-to-drain connection, we employ ground elevation together with cities drainage channel maps, validated by Google Street View where available.

The assumption that every building has a septic tank or is connected to a drain, is most likely an overestimation of reality. There will be buildings with no toilets at all, although given the nature of the build-up, this is unlikely in the current study

area but should be carefully considered if the approach is adopted in other areas. Another example of the assumption is the usage of a soak pit when there is no storm drainage in the street or when the drain is too far away from the building to connect. The sub catchment area to which the prototype has been applied is built-up with a well-developed drain network and little space for soak pits. Therefore, the number of soak pits in the sub-catchment area is expected to be very low as has been identified in Dhaka (Foster et al., 2021) and so this assumption will hold. In other parts of the city where soak pits are used the impact on the output will be greater as the liquid portion of waste will go to the soak pit and stored solids are more likely to be emptied and taken away instead of ending up in drains. Also, current evidence suggests that septic tank emptying is neither frequent nor common (Bari, 2017) and therefore when septic tanks have reached their design storage capacity their solids removal performance will be reduced and solids release to the storm drain will increase.

There is significant reason to believe that there are important exports of sludge from the drain network through drain scraping and potentially unplanned losses through flooding and sediment redistribution which current model is not taking into account.

2.8.3 Implications and outlook

Until now, sanitation has been scaled up to the city level, implying that we have knowledge of a city's sanitation status (Peal et al., 2014, 2020). However, many governments, lack the capacity to provide sanitation on a large scale, particularly at the secondary cities.

This study is critical for developing a better understanding of the spatial sanitation situation in cities, which will help to reduce the gap in wastewater and faecal sludge management prioritising, planning, and decision making.

The purpose of spatial representation is to provide a credible approach to locate faecal sources and movement pathways for a better understanding of the potential areas of faecal accumulation. It provides a characterisation and understanding of sanitation system of the city beyond what current tools are

capable of, necessary for effective management and prioritisation of resources. Normally, to solve the sanitation issue, city authorities typically handle faecal matter and drains in a reactive manner, only taking action when there is a problem, rather than proactively maintaining the drains to prevent them from being blocked and/or overflow. This approach is inefficient and ineffective as it does not address the root cause and does not prevent future problems. A proactive approach that tackles both short-term and long-term challenges can be developed by using the spatial representation technique we describe here. Short-term adjustments might include changes in faecal management behaviours, such as the frequency of septic tank emptying, while long-term strategies could address the implications of population growth and increased building construction. Adapting the SanIFFlow approach to future scenarios involves updating the model parameters within a GIS framework to reflect changes in population density. This adaptability can ensure that the model remains relevant and useful in ongoing urban planning and infrastructure development.

Although we have demonstrated the spatial representation, more research into analysing uncertainties and determining the sensitivity of assumptions, as well as field validation, is required for the methodology.

2.9 Conclusions

Here we developed a prototype method to make use of free and open datasets and provide answers to the spatial scale characterisation of faecal production and mobility in urban settings in data-poor areas of economically developing countries. It also improved our understanding of the spatial aspects of urban sanitation in terms of faecal movement pathways and areas of faecal concentration. The intended methodology, once the uncertainties are addressed, will provide information to the city authority, environmental agency as well as sanitation professionals to understand the connection between sources, pathways and receptors of faecal pollution, potential pollution hotspot and sanitation service provisions in a low and middle-income urban setting.

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References

- Alam, M.-U., Sharior, F., Ferdous, S., Ahsan, A., Ahmed, T., Afrin, A., Sarker, S., Akand, F., Archie, R. J., Hasan, K., Renouf, R., Drabble, S., Norman, G., Rahman, M., & Tidwell, J. B. (2020). Strategies to Connect Low-Income Communities with the Proposed Sewerage Network of the Dhaka Sanitation Improvement Project, Bangladesh: A Qualitative Assessment of the Perspectives of Stakeholders. *International Journal of Environmental Research and Public Health*, 17(19), 7201. <https://doi.org/10.3390/ijerph17197201>
- Amin, N., Liu, P., Foster, T., Rahman, M., Miah, M. R., Ahmed, G. B., Kabir, M., Raj, S., Moe, C. L., & Willetts, J. (2020). Pathogen flows from on-site sanitation systems in low-income urban neighborhoods, Dhaka: A quantitative environmental assessment. *International Journal of Hygiene and Environmental Health*, 230, 113619. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113619>
- ASF DAAC. (2015). *ALOS PALSAR Radiometric Terrain Corrected high resolution*. The ASF (Alaska Satellite Facility) Distributed Active Archive Center (DAAC). <https://doi.org/10.5067/Z97HFCNKR6VA>
- Barbosa, A. E., Fernandes, J. N., & David, L. M. (2012). Key issues for sustainable urban stormwater management. *Water Research*, 46(20), 6787–6798. <https://doi.org/10.1016/j.watres.2012.05.029>
- Bari, M. N. (2017). Study on Existing Faecal Sludge Management Situation in Rajshahi Rajshahi City. *Proceedings of the WasteSafe 2017 – 5th*

International Conference on Solid Waste Management in South Asian Countries 25-27 February 2017, Khulna, Bangladesh STUDY, March.

Bari, M. N., & Kabir, M. R. (2023). *Urban Sanitation Facilities and Its Management in Rajshahi City Urban Sanitation Facilities and Its Management in Rajshahi City. November.*

Bari, N., Bushra, A., & Zaman, J. (2018). Management of faecal sludge by rajshahi city corporation. *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development, July, 1–11.*
http://www.iccesd.com/proc_2018/Papers/r_p4803.pdf

BBS. (2005). *Statistical Yearbook of Bangladesh. Bangladesh Bureau of Statistics.*

BBS. (2013). *Rajshahi District Statistics 2011 (Issue June).*

Berendes, D. M., Sumner, T. A., & Brown, J. M. (2017). Safely Managed Sanitation for All Means Fecal Sludge Management for At Least 1.8 Billion People in Low and Middle Income Countries. *Environmental Science & Technology, 51(5), 3074–3083.* <https://doi.org/10.1021/acs.est.6b06019>

Blackett, I., Hawkins, P., & Heymans, C. (2014). *The Missing Link in Sanitation Service Delivery: A Review of Fecal Sludge Management in 12 Cities.*
<https://doi.org/10.13140/RG.2.1.4072.7205>

Bustos, M. F. A., Hall, O., Niedomysl, T., & Ernstson, U. (2020). A pixel level evaluation of five multitemporal global gridded population datasets: a case study in Sweden, 1990–2015. *Population and Environment, 42(2), 255–277.*
<https://doi.org/10.1007/s11111-020-00360-8>

Capodaglio, A. G., Callegari, A., Cecconet, D., & Molognoni, D. (2017). Sustainability of decentralized wastewater treatment technologies. *Water Practice and Technology, 12(2), 463–477.*
<https://doi.org/10.2166/wpt.2017.055>

Clemett, A., Amin, M., & Ara, S. (2006). *Background Information for Rajshahi City*

, Bangladesh.

- Coetzee, S., Ivánová, I., Mitasova, H., & Brovelli, M. A. (2020). Open Geospatial Software and Data: A Review of the Current State and A Perspective into the Future. *ISPRS International Journal of Geo-Information*, 9(2). <https://doi.org/10.3390/ijgi9020090>
- CWAS. (2020). *Using Sani Tab for monitoring scheduled emptying operations in two cities in Maharashtra – Wai and Sinnar*. https://pas.org.in/Portal/document/UrbanSanitation/uploads/sanitab_slide_deck_part_2_9dec.pdf
- Deng, Z., Huang, D., He, Q., & Chassagne, C. (2022). Review of the action of organic matter on mineral sediment flocculation. *Frontiers in Earth Science*, 10. <https://doi.org/10.3389/feart.2022.965919>
- Dissanayake, Amin, M. M., Amerasinghe, P., & Clemett, A. (2007). Baseline Water Quality Survey for Rajshahi, Bangladesh. In *WASPA Asia: Project Report 7*.
- Ekklesia, E., Shanahan, P., Chua, L. H. C., & Eikaas, H. S. (2015). Temporal variation of faecal indicator bacteria in tropical urban storm drains. *Water Research*, 68, 171–181. <https://doi.org/https://doi.org/10.1016/j.watres.2014.09.049>
- Englund, M., Carbajal, J. P., Ferré, A., Bassan, M., Hoai Vu, A. T., Nguyen, V.-A., & Strande, L. (2020). Modelling quantities and qualities (Q&Q) of faecal sludge in Hanoi, Vietnam and Kampala, Uganda for improved management solutions. *Journal of Environmental Management*, 261, 110202. <https://doi.org/https://doi.org/10.1016/j.jenvman.2020.110202>
- ESRI. (2019). *Understanding the Utility Network: A Guide for Water Utilities*. <https://www.esri.com/en-us/landing-page/industry/water/2019/understanding-utility-network>
- Ezechiel, N., & Baptiste Safari, J. (2020). Assessing the Impact of Secondary City Development on Sanitation Services: The Case of Muhanga District 2013-

2017. *International Journal of Natural Resource Ecology and Management*, 5(3), 90. <https://doi.org/10.11648/j.ijnrem.20200503.12>
- Fisher, P. (1997). The pixel: A snare and a delusion. *International Journal of Remote Sensing*, 18(3), 679–685. <https://doi.org/10.1080/014311697219015>
- Foster, T., Falletta, J., Amin, N., Rahman, M., Liu, P., Raj, S., Mills, F., Petterson, S., Norman, G., Moe, C., & Willetts, J. (2021). Modelling faecal pathogen flows and health risks in urban Bangladesh: Implications for sanitation decision making. *International Journal of Hygiene and Environmental Health*, 233, 113669. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113669>
- Gambrill, M., Gilsdorf, R. J., & Kotwal, N. (2020). Citywide Inclusive Sanitation—Business as Unusual: Shifting the Paradigm by Shifting Minds. *Frontiers in Environmental Science*, 7(February), 1–10. <https://doi.org/10.3389/fenvs.2019.00201>
- Gil, J., Beirão, J. N., Montenegro, N., & Duarte, J. P. (2012). On the discovery of urban typologies: Data mining the many dimensions of urban form. *Urban Morphology*, 16(1), 27–40. <https://doi.org/10.51347/jum.v16i1.3966>
- Google. (n.d.). *Google Earth Pro v.7.3.4.8248 (64-bit)*. Retrieved January 17, 2021, from kh.google.com
- Greger, K. (2015). Spatio-temporal building population estimation for highly urbanized areas using GIS. *Transactions in GIS*, 19(1), 129–150. <https://doi.org/10.1111/tgis.12086>
- Hawkins, P., & Muxímpua, O. (2015). Developing Business Models for Fecal Sludge Management in Maputo. In *Water and Sanitation Program* (Issue June). <https://wsp.org/sites/wsp.org/files/publications/WSP-Developing-Business-Models-for-Fecal-Sludge-Management-Maputo.pdf>
- HBRI. (2015). *Bangladesh National Building Code*.
- Hyun, C., Burt, Z., Crider, Y., Nelson, K. L., Prasad, C. S. S., Rayasam, S. D. G.,

- Tarpeh, W., & Ray, I. (2019). Sanitation for Low-Income Regions: A Cross-Disciplinary Review. *Annual Review of Environment and Resources*, 44(1), 287–318. <https://doi.org/10.1146/annurev-environ-101718-033327>
- IRC. (2017). *Faecal Waste Flow Calculator*. <https://www.ircwash.org/tools/faecal-waste-flow-calculator>
- Islam, M. S., Islam, S. M., & Islam, A. M. (2021). Assessment of efficacy of drainage system in Rajshahi City Corporation, Bangladesh. *Advances in Environmental Research*, 10(2), 105–116. <https://doi.org/10.12989/aer.2021.10.2.105>
- Jenks, G. F. (1977). Optimal data classification for choropleth maps. *Department of Geography, University of Kansas Occasional Paper*.
- Jenson, S. K., & Domingue, J. O. (1988). Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing*, 54(11), 1593–1600.
- Kaupp, R. (2016). *Comparison of tools & approaches for urban sanitation September 2016 Introduction*. <https://policycommons.net/artifacts/2333103/comparison-of-tools-approaches-for-urban-sanitation-september-2016-introduction/3093766/>
- Kelkar, V., & Seetha Ram, K. (2019). a Literature Review Evaluating New Approaches To Resolving the Sanitation Challenge in Developing Asia. In *ADB Working Paper Series* (Issue 976). <https://www.adb.org/publications/evaluating->
- Koné, D. (2010). Making urban excreta and wastewater management contribute to cities' economic development: a paradigm shift. *Water Policy*, 12(4), 602–610. <https://doi.org/10.2166/wp.2010.122>
- Leidig, M., Teeuw, R. M., & Gibson, A. D. (2016). Data poverty: A global evaluation for 2009 to 2013 - implications for sustainable development and disaster risk reduction. *International Journal of Applied Earth Observation and Geoinformation*, 50, 1–9.

<https://doi.org/https://doi.org/10.1016/j.jag.2016.03.001>

- Leong, W. K., Ngo, A. L. K., Wong, A. C. H., Ling, J. H., & Sia, H. T. (2022). The Mandatory 4 Years Desludging Frequency of Underground Septic Tanks in Residential Areas: A Case Study in Sibu Sarawak, East Malaysia. *Journal of the Civil Engineering Forum*, 8(2 SE-Articles). <https://doi.org/10.22146/jcef.3812>
- Leyk, S., Gaughan, A. E., Adamo, S. B., de Sherbinin, A., Balk, D., Freire, S., Rose, A., Stevens, F. R., Blankespoor, B., Frye, C., Comenetz, J., Sorichetta, A., MacManus, K., Pistolessi, L., Levy, M., Tatem, A. J., & Pesaresi, M. (2019). The spatial allocation of population: a review of large-scale gridded population data products and their fitness for use. *Earth System Science Data*, 11(3), 1385–1409. <https://doi.org/10.5194/essd-11-1385-2019>
- Li, C., Fan, Z., Wu, Z., Dai, Z., Liu, L., & Zhang, C. (2020). Methodology of sub-catchment division considering land uses and flow directions. *ISPRS International Journal of Geo-Information*, 9(11). <https://doi.org/10.3390/ijgi9110634>
- Luthi, C., Morel, A., Kohler, P., & Tilley, E. (2009). *People's Choice First: A 4-Country Comparative Validation of the HCES Planning Approach for Environmental Sanitation*.
- Lüthi, C., Willetts, J., & Hoffmann, S. (2020). Editorial: City-Wide Sanitation: The Urban Sustainability Challenge. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.585418>
- Mansour, G., & Esseku, H. (2017). Situation analysis of the urban sanitation sector in Ghana. *WSUP - Water & Sanitation for the Urban Poor*, July, 27.
- Marais, L., & Cloete, J. (2017). The role of secondary cities in managing urbanisation in South Africa. *Development Southern Africa*, 34(2), 182–195. <https://doi.org/10.1080/0376835X.2016.1259993>
- Mehta, M., Mehta, D., & Yadav, U. (2019). Citywide Inclusive Sanitation Through

- Scheduled Desludging Services: Emerging Experience From India. *Frontiers in Environmental Science*, 7. <https://doi.org/10.3389/fenvs.2019.00188>
- Mills, F., Willetts, J., Petterson, S., Mitchell, C., & Norman, G. (2018). Faecal pathogen flows and their public health risks in urban environments: A proposed approach to inform sanitation planning. *International Journal of Environmental Research and Public Health*, 15(2). <https://doi.org/10.3390/ijerph15020181>
- Mtika, W. M., & Tilley, E. (2020). Environmental Sanitation Planning: Feasibility of the CLUES Framework in a Malawian Small Town. *Frontiers in Environmental Science*, 7. <https://doi.org/10.3389/fenvs.2019.00204>
- Müller, A., Österlund, H., Marsalek, J., & Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. *Science of The Total Environment*, 709, 136125. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.136125>
- Narayan, A. S., Fischer, M., & Lüthi, C. (2020). Social Network Analysis for Water, Sanitation, and Hygiene (WASH): Application in Governance of Decentralized Wastewater Treatment in India Using a Novel Validation Methodology. *Frontiers in Environmental Science*, 7(January). <https://doi.org/10.3389/fenvs.2019.00198>
- Niwagaba, C. B., Mbéguéré, M., & Strande, L. (2014). Faecal Sludge Quantification, Characterisation and Treatment Objectives. In L. Strande, M. Ronteltap, & D. Brdjanovic (Eds.), *Faecal Sludge Management Systems Approach for Implementation and Operation* (pp. 19–44). IWA Publishing.
- Opel, A., Bashar, M. K., & Ahmed, M. F. (2012). Faecal sludge management in Bangladesh : an issue that needs urgent attention. *Asia Regional Sanitation and Hygiene Prtitioners Workshop, February*, 1–9.
- OpenStreetMap Contributors. (2019). *Planet.osm*. <https://planet.openstreetmap.org/>
- Otis, R. J., & Sirotiak, K. (1987). Sewer-Septic Tank Hybrid Promises Savings.

- Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Services Research*, 34(5 Pt 2), 1189.
- Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., Schoebitz, L., Scott, R., Sleigh, A., Strande, L., & Veses, O. (2020). Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned From a Global Implementation of Excreta-Flow Diagrams. *Frontiers in Environmental Science*, 8, 1. <https://doi.org/10.3389/fenvs.2020.00001>
- Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2014). Fecal sludge management (FSM): analytical tools for assessing FSM in cities. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 371–383. <https://doi.org/10.2166/washdev.2014.139>
- Qasem, N. A. A., Mohammed, R. H., & Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: a comprehensive and critical review. *Npj Clean Water*, 4(1). <https://doi.org/10.1038/s41545-021-00127-0>
- Quang, C. N. X., Giang, N. N. H., Hoa, H. V, & Hung, P. Q. (2022). Effects of sediment deposit on the hydraulic performance of the urban stormwater drainage system. *IOP Conference Series: Earth and Environmental Science*, 964(1), 12020. <https://doi.org/10.1088/1755-1315/964/1/012020>
- Rahaman, M. F., Ali, M. S., Arefin, R., Mazumder, Q. H., Majumder, R. K., & Jahan, C. S. (2020). Assessment of drinking water quality characteristics and quality index of Rajshahi city, Bangladesh. *Environment, Development and Sustainability*, 22(5), 3957–3971. <https://doi.org/10.1007/s10668-019-00366-9>
- Raj, S. J., Wang, Y., Yakubu, H., Robb, K., Siesel, C., Green, J., Kirby, A., Mairinger, W., Michiel, J., Null, C., Perez, E., Roguski, K., & Moe, C. L. (2020). The SaniPath Exposure Assessment Tool: A quantitative approach for assessing exposure to fecal contamination through multiple pathways in

- low resource urban settlements. *PLoS ONE*, 15(6), 1–18.
<https://doi.org/10.1371/journal.pone.0234364>
- Rasul, M. T., & Jahan, M. S. (2010). Quality of Ground and Surface Water of Rajshahi City Area for Sustainable Drinking Water Source. *Journal of Scientific Research*, 2(3), 577. <https://doi.org/10.3329/jsr.v2i3.4093>
- Robb, K., Null, C., Teunis, P., Yakubu, H., Armah, G., & Moe, C. L. (2017). Assessment of fecal exposure pathways in low-income urban neighborhoods in Accra, Ghana: rationale, design, methods, and key findings of the Sanipath study. *American Journal of Tropical Medicine and Hygiene*, 97(4), 1020–1032. <https://doi.org/10.4269/ajtmh.16-0508>
- Rodriguez, F., Le Delliou, A.-L., Andrieu, H., & Gironás, J. (2020). Groundwater Contribution to Sewer Network Baseflow in an Urban Catchment-Case Study of Pin Sec Catchment, Nantes, France. In *Water* (Vol. 12, Issue 3). <https://doi.org/10.3390/w12030689>
- Roldin, M., Fryd, O., Jeppesen, J., Mark, O., Binning, P. J., Mikkelsen, P. S., & Jensen, M. B. (2012). Modelling the impact of soakaway retrofits on combined sewage overflows in a 3km² urban catchment in Copenhagen, Denmark. *Journal of Hydrology*, 452–453, 64–75. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2012.05.027>
- Rose, A. N., McKee, J. J., Sims, K. M., Bright, E. A., Reith, A. E., & Urban, M. L. (2020). *LandScan 2019* (2019 RI-). Oak Ridge National Laboratory SE - July 1, 2020. <https://landscan.ornl.gov/>
- Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Critical Reviews in Environmental Science and Technology*, 45(17), 1827–1879. <https://doi.org/10.1080/10643389.2014.1000761>
- RWASA. (2022). *Yearly Report 2021-2022 (Bengali)*. <http://rajshahiwasaportal.gov.bd/sites/default/files/files/rajshahiwasaportal>

gov.bd/page/475e362d_7060_4662_9fc4_ce5da8acf69c/2022-10-16-04-40-a2a51c26c52a31be0cc2a9c3cd19ae76.pdf

- Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Espeland, W., Kay, J., Lo Piano, S., Mayo, D., Jr, R., Portaluri, T., Porter, T., Puy, A., Rafols, I., Ravetz, J., Reinert, E., Sarewitz, D., Stark, P., & Vineis, P. (2020). Five ways to ensure that models serve society: a manifesto. *Nature*, 582, 482–484. <https://doi.org/10.1038/d41586-020-01812-9>
- Salvadore, E., Bronders, J., & Batelaan, O. (2015). Hydrological modelling of urbanized catchments: A review and future directions. *Journal of Hydrology*, 529, 62–81. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2015.06.028>
- Schmidt, M. (2008). The Sankey Diagram in Energy and Material Flow Management. *Journal of Industrial Ecology*, 12(2), 173–185. <https://doi.org/https://doi.org/10.1111/j.1530-9290.2008.00015.x>
- Schrecongost, A., Pedi, D., Rosenboom, J. W., Shrestha, R., & Ban, R. (2020). Citywide Inclusive Sanitation: A Public Service Approach for Reaching the Urban Sanitation SDGs. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00019>
- Scott, P., & Cotton, A. P. (2020). The Sanitation Cityscape – Toward a Conceptual Framework for Integrated and Citywide Urban Sanitation. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00070>
- Scott, P., Cotton, A., & Sohail, M. (2015). Using tenure to build a “sanitation cityscape”: narrowing decisions for targeted sanitation interventions. *Environment and Urbanization*, 27(2), 389–406. <https://doi.org/10.1177/0956247815569415>
- Sercu, B., Van De Werfhorst, L. C., Murray, J. L. S., & Holden, P. A. (2011). Sewage Exfiltration As a Source of Storm Drain Contamination during Dry Weather in Urban Watersheds. *Environmental Science & Technology*, 45(17), 7151–7157. <https://doi.org/10.1021/es200981k>

- Setty, K., Jiménez, A., Willetts, J., Leifels, M., & Bartram, J. (2020). Global water, sanitation and hygiene research priorities and learning challenges under Sustainable Development Goal 6. *Development Policy Review*, 38(1), 64–84. <https://doi.org/https://doi.org/10.1111/dpr.12475>
- Shawky, M., Moussa, A., Hassan, Q. K., & El-Sheimy, N. (2019). Pixel-Based Geometric Assessment of Channel Networks/Orders Derived from Global Spaceborne Digital Elevation Models. *Remote Sensing*, 11(3). <https://doi.org/10.3390/rs11030235>
- Spuhler, D., & Lüthi, C. (2020). Review of frameworks and tools for urban strategic sanitation planning: considering technology innovations and sustainability. *Journal of Water, Sanitation and Hygiene for Development*, 10(4), 768–785. <https://doi.org/10.2166/washdev.2020.062>
- Strahler, A. (1952). Dynamic Basis of Geomorphology. *GSA Bulletin*, 63(9), 923–938. [https://doi.org/10.1130/0016-7606\(1952\)63\[923:DBOG\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1952)63[923:DBOG]2.0.CO;2)
- Strande, L., Evans, B., von Sperling, M., Bartram, J., Harada, H., Nakagiri, A., & Nguyen, V.-A. (2023). Urban Sanitation: New Terminology for Globally Relevant Solutions? *Environmental Science & Technology*, 0(0), null. <https://doi.org/10.1021/acs.est.3c04431>
- Strande, L., Ronteltap, M., & Brdjanovic, D. (2014). *Faecal Sludge Management – Systems Approach for Implementation and Operation*. IWA Publishing. <https://doi.org/10.2166/9781780404738>
- Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B. J., & Niwagaba, C. B. (2018). Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions. *Journal of Environmental Management*, 223(June), 898–907. <https://doi.org/10.1016/j.jenvman.2018.06.100>
- Strande, L., Velkushanova, K., & Brdjanovic, D. (2021). Setting the stage. In B. D. and B. C. Velkushanova K., Strande L., Ronteltap M., Koottatep T. (Ed.), *Methods for Faecal Sludge Analysis* (pp. 1–14). IWA Publishing.

- Sultana, M. S., Waine, T., Bari, N., & Tyrrel, S. (2023). Towards a new spatial representation of faecal sources and pathways in unsewered urban catchments using open-source data. *Journal of Water, Sanitation and Hygiene for Development*, 13(4), 289–300. <https://doi.org/10.2166/washdev.2023.227>
- Tabassum, S. (2020). Drainage system, its water quality and health effect: A case study of Rajshahi city, Bangladesh. *Scientific Journal of Environmental Sciences*, 9(1), 323–336. <https://doi.org/10.14196/sjes.v9i1.2612>
- Tague, N. R. (2005). *The Quality Toolbox* (2nd ed.). ASQ Quality Press.
- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P., Schertenleib, R., & Zurbrugg, C. (2014). *Compendium of Sanitation Systems and Technologies* (2nd Revise). Swiss Federal Institute of Aquatic Science and Technology (Eawag).
- UNICEF/WHO. (2023). *Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender*. United Nations Children’s Fund (UNICEF) and World Health Organization (WHO). https://washdata.org/sites/default/files/2022-01/jmp-2021-wash-households_3.pdf
- Vandenbulcke, L., & Barth, A. (2019). Upscaling of a local model into a larger-scale model. *Ocean Science*, 15(2), 291–305. <https://doi.org/10.5194/os-15-291-2019>
- Vu, T. T., Vu, N. V. A., Phung, H. P., & Nguyen, L. D. (2021). Enhanced urban functional land use map with free and open-source data. *International Journal of Digital Earth*, 14(11), 1744–1757. <https://doi.org/10.1080/17538947.2021.1970262>
- Walters, P. (2018). The limits to participation: Urban poverty and community driven development in Rajshahi City, Bangladesh. *Community Development*, 49(5), 539–555. <https://doi.org/10.1080/15575330.2018.1537296>
- WaterAid. (2018). *SFD Lite Report of Rajshahi City Corporation Bangladesh*.

- WaterAid. (2021). *WaterAid, Bangladesh and SDG 6. September*, 1–9. <https://www.wateraid.org/bd/wateraid-bangladesh-everyone-everywhere-by-2030>
- Whittington, D., Lauria, D. T., Choe, K., Hughes, J. A., Swarna, V., & Wright, A. M. (1993). Household sanitation in Kumasi, Ghana: A description of current practices, attitudes, and perceptions. *World Development*, 21(5), 733–748. [https://doi.org/10.1016/0305-750X\(93\)90030-D](https://doi.org/10.1016/0305-750X(93)90030-D)
- Willetts, J., Mills, F., & Al'Afghani, M. (2020). Sustaining Community-Scale Sanitation Services: Co-management by Local Government and Low-Income Communities in Indonesia. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00098>
- Woolley, S. M., Buckley, C. A., Pocock, J., & Foutch, G. L. (2014). Rheological modelling of fresh human faeces. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 484–489. <https://doi.org/10.2166/washdev.2014.088>
- World Bank. (2003). *Enabling Environments for Civic Engagement in PRSP Countries*. <http://hdl.handle.net/10986/11319>
- Zeng, C., Wang, J., Zhan, W., Shi, P., & Gambles, A. (2014). An elevation difference model for building height extraction from stereo-image-derived DSMs. *International Journal of Remote Sensing*, 35. <https://doi.org/10.1080/01431161.2014.975375>

3 AN ANALYSIS OF FACTORS THAT INFLUENCE THE SPATIAL PATTERN OF FAECAL MATTER FLOW IN UNSEWERED CITIES³

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3.1 Highlights

- Innovative GIS-based sanitation analysis in unsewered urban areas
- Paper identifies five key factors influencing faecal matter flow in cities.
- Factors, while individually minor, collectively change faecal flow by 50%.
- Study guides future spatial data collection on urban faecal matter movement.

3.2 Abstract

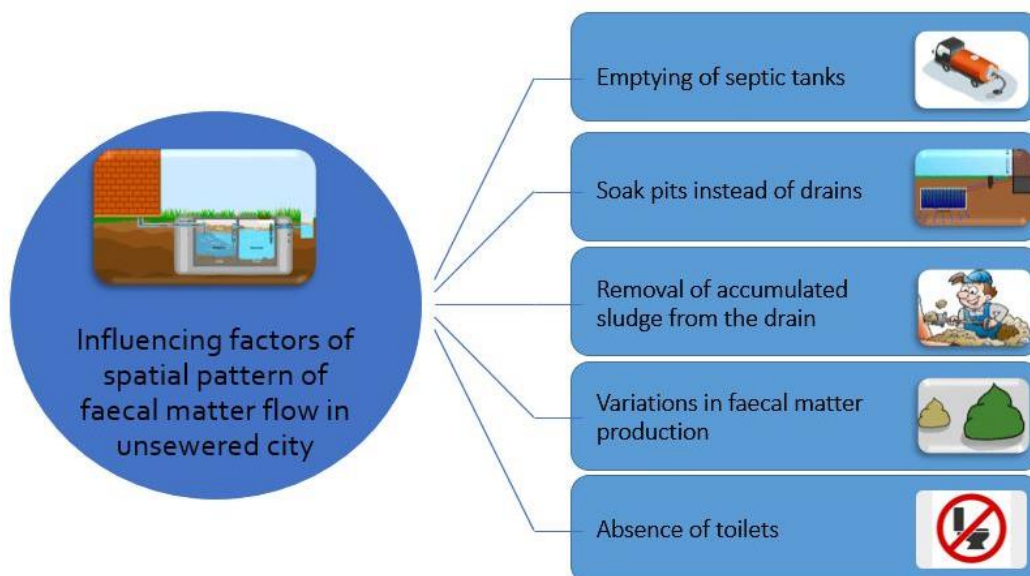
The management of sanitation systems in unsewered cities in economically developing countries is a critical issue, yet it is unclear where the risk hotspots are and where interventions should be focused. This study utilised a prototype model, developed by the authors, to map the spatial pattern of faecal flow in Rajshahi city, a secondary city in northwest Bangladesh with a population around a million. This city serves as a representative example of 60 such secondary cities

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in Bangladesh and hundreds more in the economically developing region in Asia, Africa and Latin America. The model relies on assumptions that carry significant uncertainties; hence, the study employed a sensitivity analysis with multiple plausible scenarios to characterise these uncertainties, aiming to identify ways to improve the model further. Five major influencing factors on the spatial pattern of faecal flow were identified: the emptying of septic tanks, the use of soak pits, and sludge removal from drains, variations in faecal matter production by building types, and the presence or absence of toilets. These factors were shown to collectively have a significant impact (almost 50% changed) on the model outcome, depending upon the assumptions made. The study offers insights that will guide future data collection efforts by emphasising the need to understand these specific influencing factors and their spatial pattern. Consequently, this research has broader implications for urban sanitation management as well as associated public health research like wastewater surveillance, risk assessment, and disease dynamics in similar urban settings, offering insights into areas of uncertainty that need to be addressed in future modelling efforts.

Keywords: unsewered cities, uncertainty, spatial faecal flow, Bangladesh, open-source data

3.3 Graphical Abstract



3.4 Introduction

There are hundreds of cities with populations of around million or more, where sanitation management is a major issue. City-wide management is a major challenge as sanitation is individually owned and maintained using septic tanks and pits (Strande et al., 2018) resulting in a system which is hard to characterise and whose behaviour is hard to predict. Wastewater is managed through local drains which were not designed for this purpose since the sanitation service chain does not exist and there is not enough sewer infrastructure (Mills et al., 2018). Additionally, most septic tanks are not regularly emptied (Bari, 2017; Mehta et al., 2019), which causes a fraction of faecal matter to overflow with wastewater. This can result in sludge accumulation in some parts of the city, which can be hazardous to human health (Raj et al., 2020). Furthermore, extreme weather events such as floods or heavy rain can exacerbate these risks, increasing the likelihood of health consequences for those living in affected areas (Foster et al., 2021; Tabassum, 2020). Fixing the sanitation problem for an entire city takes a significant amount of time, resources, expertise, and data; and as a result, many cities lack a sanitation management framework (Blackett et al., 2014; Koné, 2010).

Recent studies in Bangladesh, where nearly one-third of urban residents lack access to safely managed sanitation, have emphasized the importance of understanding pathogen flows from on-site sanitation systems, especially in densely populated urban areas (Alam et al., 2020; Amin et al., 2020; Foster et al., 2021). These researches reveal high concentrations of pathogens in environmental samples, demonstrating the need for comprehensive sanitation management (Amin et al., 2020). Foster et al. (2021) further highlight the significant role of modelling in assessing public health impacts and guiding sanitation decisions. These insights underline the urgent need for robust, data-driven models that can navigate the complexities of urban sanitation in Bangladesh. These challenges are exacerbated by policy and financial constraints, particularly in low-income communities (Alam et al., 2020).

Several sanitation assessment tools have been developed and are currently available to provide a comprehensive understanding of the sanitation status of an entire city, including reliable methods to estimate total accumulated quantities and qualities of faecal sludge (Peal et al., 2020; Strande et al., 2018). However, the lack of data often makes it difficult for generalising the methodology, incorporating more real-time data, linking to fundamental models, as well as spatially represent the sanitary infrastructure in cities (Leidig et al., 2016).

To address this challenge, the authors developed a new methodology utilising open-source data to spatially represent sanitation systems (Sultana et al., 2023) which offers an important step in this field. In the study, Rajshahi, a city located in northwest Bangladesh (WaterAid, 2018) was used as an example to address the problem faced by hundreds of secondary cities. The methodology identified faecal matter sources and movement pathways by assigning the population to each building based on its volume, and utilising network modelling to estimate faecal movement from buildings to the catchment outlet through the drains (Sultana et al., 2023). However, like any model this had to have several assumptions (e.g., Saltelli et al., 2020) faecal matter generated in buildings ends up in local drains and then flows to the catchment outlet, however, this is unlikely to be the case in the real world. Due to the individual management systems in place, some people may choose to empty their septic tanks, which has no impact on the drain, and there may also be soak pits that have no influence on the drain. Therefore, the spatial pattern of faecal movement depends on several factors, which can often be generalized or uniformly simplified, leading to uncertainties and inadequate representation. Characterising the spatial dynamics of the factors that impact faecal flow may help to improve future applications of the model in other cities.

Therefore, this paper aims to evaluate the influence of different assumptions and uncertainties on the model's outcomes. It examines the assumptions which impact the faecal production sources and the movement pathways, filling gaps in understanding of spatial variability in faecal matter movement pattern in unsewered urban sanitation. In this study, we focus again on Rajshahi city to

showcase how different assumptions and uncertainties can influence the outcome of the spatial representation. It can be noted that, in the model faecal mass has been used as an indicator, this tool that can be used to support sanitation interventions as well as public health research like wastewater surveillance, risk assessment, and disease dynamics. This paper will help to refine the model for future applications in other cities, keeping in line with the findings from Foster et al., 2021 about the usefulness of such models in sanitation decision-making.

3.5 Method

This chapter is designed to address and assess the uncertainty of the spatial pattern of faecal production and movement. Five factors were identified by a qualitative assessment of the uncertainty and ranking the influence of the assumptions Table B- 1 in the appendix on the spatial faecal mass production and movement. Then a sensitivity analysis has been done to quantify the influence of those factors. The empirical data of those factors composed from the literature, anecdotal evidence and assumptions from Rajshahi City in conjunction with relevant secondary data sources (Sultana et al., 2023). This integrated approach allows to evaluate the influence of different assumptions and uncertainties on the model's outcomes. The method comprised three major steps: First, i) identifying important influencing factors. Second, ii) analysing the sensitivity of each factor and finally, iii) assessed the combined influence of all factors and comparing the model outcome with base case model output.

3.5.1 Data Integration

The model integrates diverse data sources to estimate population distribution, faecal production per building, and the connectivity from buildings to drains, subsequently visualising this data through a faecal mass flow map (Sultana et al., 2023). The study employs GIS techniques for the analysis and model development (Figure 3.1). Data from OpenStreetMap (OpenStreetMap Contributors., 2019), LandScan (Rose et al., 2020), and ALOS PALSAR DEM (ASF DAAC, 2015) are combined to estimate the population within buildings and calculate faecal mass based on a standardised per capita production rate. Also,

utilising drainage maps of the city to link buildings to the nearest drain to infer flow directions.

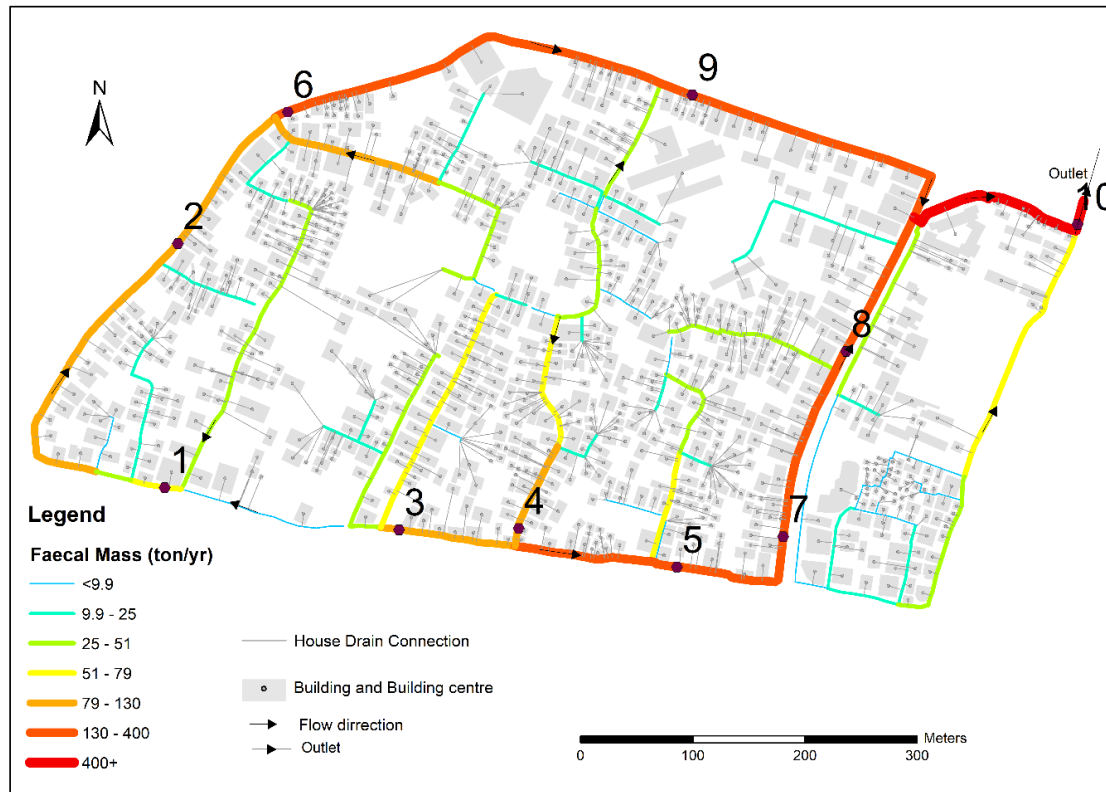


Figure 3.1: The spatial pattern of faecal flow in an unsewered urban catchment Kazihata, Rajshahi (Sultana et al., 2023). Here we can see ten observation points that were used in the sensitivity analysis.

3.5.2 Data analysis

A protocol has been designed to assess the sensitivity of the influencing factors with various alternative assumptions by contrasting the outcomes against the base-case model. To measure the impact of these alternative assumptions, ten observation points have been selected across the model area, including one close to the outflow of the catchment (Figure 3.1). The selection of ten observation points was designed to capture the spatial variability in faecal mass flow across the model area. These points were carefully placed to include a mix of outlets of mini service areas (specifically points 1, 3, and 4). A mini service area typically comprises a small drain that handles wastewater from a few households. The remaining points (2, 5, 6, 7, 8, 9, and 10) were located near clusters of such

service areas, where secondary and primary drains aggregate wastewater from multiple smaller drains. The intention of this approach was to help to visualize the impact on the model output of the varied urban context and sanitation dynamics within the study area.

3.5.3 Identifying influencing factors

In developing the base case model, ten assumptions were made due to unavailability of field data on local sanitation practices and infrastructure. A detailed list of these assumptions and their qualitative evaluation can be found in Table B- 2 in the appendix and the summarised version in (Figure 3.2). This qualitative analysis enabled us to categorise the assumptions into classes based on their assessed influence: low, moderate, or high. This step was crucial for identifying the major influencing factors of faecal mass flow variability.

During the evaluation process, certain assumptions were excluded if they were determined to have minimal influence on the spatial variability of faecal matter flow or if the required data was unavailable. For example, assumption number 2, “Septic tanks are located at the centre of each plot” was a necessary model assumption to provide a means by which to connect the septic tank to the drain. However, this assumption does not have a noticeable influence on faecal production or in the spatial movement of faecal matter flow as most of the plots are small and the real location of the septic tank will not affect the map. Given the low impact of this assumption on the map it was excluded from the subsequent analysis. Similarly with assumption 5, it is currently considered that septic tanks are so poorly designed and operated that design considerations are mostly irrelevant to the study’s outcome as well as availability of the empirical data. Also, assumptions 8, 9 and 10 were excluded because of the lack of availability of the empirical data. In doing so, five assumptions were identified which have influence on the model's outcomes. These assumptions are 1, 3, 4, 6, 7 (Figure 3.2): All buildings have toilets and septic tanks, All septic tanks are connected to drains, not soakaways, Septic tanks connected to drains are not emptied, All sludge entering drains goes to the catchment outlet, All buildings produce faecal matter, regardless of type.

3.5.4 Assessing the sensitivity of the influencing factors:

To analyse the sensitivity of the influencing factors, the empirical data was collected from existing literature, anecdotal evidence and discussion to the local professionals in Rajshahi City. The sensitivity of the five selected assumptions was analysed to define their influence on the model outputs. The overarching assumption was that all generated faecal matter in the buildings goes to the drain. Therefore, the sensitivity analysis employed alternative assumptions, to assess the outcome on the model. To do that, the prototype model does not employ a range of values for the percentage of septic tanks that are emptied or the percentage of soak pits that are used in the area because the model is intended to explore the spatial variation instead of looking at range of values. The spatial variation was assessed by employing two variants e.g., randomly selected 10% buildings and 10% buildings in a street (cluster) Table 3.1. It assumes a single value of 10% for the emptying and 10% for the soak pit use that was drawn from existing literature, as detailed in appendix (Table B-1).

How the spatial variation was looked at, for instance, the assumption that 'All septic tanks are connected to the drains,' the alternative assumption was employed that 10% buildings were using soak pit and not connected to drains. To see the spatial impact of the alternative assumption and to display this on the map there were two scenarios considered: one focusing on larger buildings. Larger buildings are defined as being those buildings with an aerial footprint in the top decile of buildings of the study area, of $> 200\text{m}^2$. Distant buildings are those furthest away from the nearest drain connection and are quantified by measuring the shortest path from the centroid of the building (a point assumed for convenience as the location of the septic tank) to the nearest drain, using GIS-based proximity analysis. For the purpose of this analysis, distant buildings are defined as being >30 m from the nearest drain. This approach offers an understanding of how each assumptions affects the spatial pattern of the model.

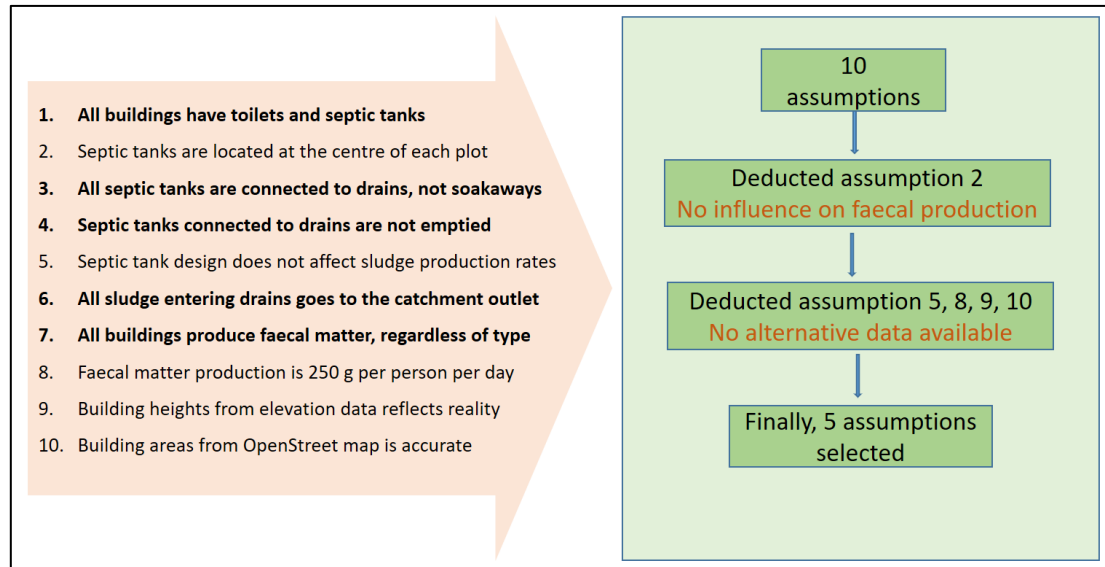


Figure 3.2: Analysing assumptions and identifying five of them which influences the spatial pattern of faecal matter flow. The left-hand side of the figure shows ten assumptions which were used to build the base case model (Sultana et al., 2023). The right-hand side panel shows briefly why some assumptions were excluded from the sensitivity analysis (detailed can be found in appendix Table B- 2). The five assumptions (influencing factors) in bold font were included in the sensitivity analysis as they were judged to be most likely to have a significant impact on the spatial pattern of faecal mass flow.

A set of alternative assumptions were developed, incorporating reasonable variations to better reflect real-world conditions. In the absence of measured data, the variants were created based on most plausible and less plausible variations to the base case model assumptions. The aim was to assess the impact of these alternative assumptions on the base case model outputs and gain a deeper understanding of their effects (Table 3.1). To address this, under the alternative assumptions, designated variants (A) with most plausible scenarios for the city and variant (B) less plausible scenarios were identified. For instance, assumption 1 "all septic tanks are connected to drains, not soak pits," an alternative assumption was created based on a statement in the provisional SFD report for Rajshahi (WaterAid, 2018) that states that 10% of the buildings have soak pits and as such are unlikely to be connected to the drain. The sensitivity analysis includes larger buildings since these are government offices

and educational institutions with space to employ soak pits and are likely to adhere to the building code (HBRI, 2015) that mandates their installation. However, to represent this spatially it is necessary to assign soak pits to buildings. In variant (A), 10% of larger buildings were assumed to have soak pits assumed they were government buildings or well-known NGOs or business centres therefore not connected to the drain. Variant (B) was based on anecdotal evidence that buildings located distant from the drains were less likely to be connected to the drains due to the cost and difficulties of connection, and thereby used soak pits to manage wastewater. Similar approaches have been used to evaluate the sensitivity of the other influencing factors in Table 3.1.

Table 3.1: Five assumptions were selected to assess their sensitivity (column 1). To do the sensitivity plausible alternative assumptions were chosen (column 2). Two scenarios, variants (A) most plausible, and variation (B) less plausible, have been produced in column 3 to assess and spatially represent alternative assumptions.

Selected assumptions	Alternative assumptions and its rational	Alternative assumptions	
		Variant (A)	Variant (B)
1) All septic tanks are connected to the drains rather than a soak pit	It is estimated that 10% of buildings in the city have a soak pit, and therefore the septic tank effluent is directed to the soak pit rather than to the drain (WaterAid, 2018).	10% of larger buildings were selected for analysis. These buildings, such as government offices, schools, colleges, and shopping malls, typically have larger areas and may utilise soak pits (Figure 3.4).	10% of distant buildings were chosen for analysis. These buildings, located far from the drain, may face cost and connectivity challenges, leading them to opt for septic tanks instead of soak pits (Figure 3.4).
2) Septic tanks connected to drains are not emptied	It is probable that up to 10% of septic tanks in the	10% of randomly selected buildings were chosen for analysis.	A spatial cluster equivalent to 10% of buildings was created

	city are emptied annually, which also preventing the faecal mass entering into the drain (Bari et al., 2018). The specific locations of these emptied septic tanks are unknown.	These buildings represent a diverse range of areas in the city, and their septic tanks are assumed to be emptied regularly. (Figure C- 1)	by selecting a single street. This can be plausible if it is made mandatory for certain type of residential areas to de sludge on a regular interval (Leong et al., 2022) e.g., government colony in cities. (Figure C- 1)
3) All of the sludge entering the drains from households is transported to the catchment outlet	The process of scraping typically occurs in areas where faecal solids accumulate, but not all of the sludge that enters the drains is completely scraped off, and not all of it reaches the catchment outlet. The actual amount of sludge that is scraped off may lie somewhere between the 25% to 75% range (Müller et al., 2020; Quang et al., 2022). To account for this variability, these fractions were assessed in	Two specific areas in the study area were chosen for assessment. Uncertainty exists over the precise volume of faecal matter that was removed from these sites and dumped at the waste disposal site. A sensitivity analysis was done to determine the probable extent of faecal matter being transported to the catchment outlet in order to address this. It was expected that the lower-bound estimate for the volume of faecal matter reaching the outlet would be 25% less than the actual Figure C- 2.	For the upper-bound estimate, it was assumed that 75% less faecal matter would actually enter the drains. This modification recognises that various factors could prevent the successful transport of all the waste material to the catchment outlet. (Figure C- 2.).

	the sensitivity analysis.		
4) Faecal matter is produced at all buildings irrespective of their types	In residential and commercial areas, faecal production will differ.	In the sensitivity analysis, the impact of this variation was assessed by considering a reduction of 25% in faecal matter production in the selected area. Roadside buildings, identified as commercial buildings using Google Street View, were chosen for the sensitivity test. The proportion of faecal output was decreased by 25% in different fractions at those locations in the model. (Figure C- 3)	In addition, a higher reduction of 75% in faecal matter production from buildings designated as commercial. (Figure C- 3)
5) Every building has a toilet and septic tank	There could be some buildings without toilets but the overall number is likely to be very low because the area is build-up and highly populated.	1% randomly selected buildings which do not have toilets (Figure C- 4)	10% randomly selected buildings which do not have toilets (Figure C- 4)

The second assumption considered the spatial variation of septic tank emptying and used two models, randomly selected 10% buildings and a cluster of 10%

buildings in a street, to capture the effect of different spatial intensities of emptying in different neighbourhoods of the city (Gil et al., 2012). The third assumption focused on identifying areas where faecal solids accumulate by using proxies, such as low slope locations and higher ratios of faecal mass flow to drain width, and considered a fractions of faecal matter scraped off at specific locations. The fourth assumption investigated the variability in faecal matter production across different types of buildings and used roadside buildings as proxies to represent commercial buildings. The fifth and final assumption considered the absence of toilets and septic tanks in randomly selected buildings, assuming that 1% and 10% of the buildings did not have these facilities, to simulate the impact on faecal production and spatial patterns.

3.5.5 The overall summary of the method

The method employed in the study is summarised in Figure 3.3. Five key assumptions (influencing factors) that affect how faecal matter move across an urban catchment area were the focus of a sensitivity analysis. Two scenarios—Variant As, which represents the most plausible set of circumstances, and Variant Bs, which shows less probable situations were considered to assess how these assumptions affect the model outcomes (Table 3.1 for details).

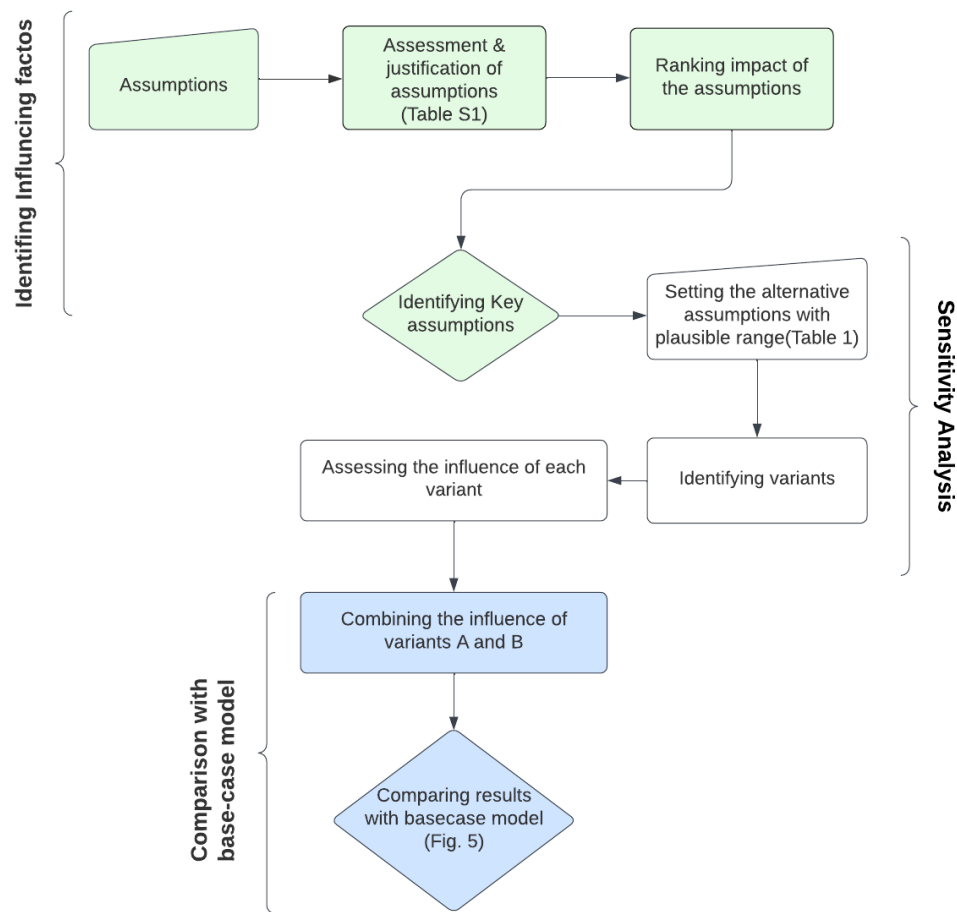


Figure 3.3: Flow chart of the methodology. There are three major steps in the analysis separated by the sheds of three colour, i) Identifying influencing factors (Key assumptions) which influences the spatial pattern of faecal matter flow (Figure 3.2), ii) Sensitivity analysis by setting up alternative assumptions with variants (Table 3.1), and finally iii) assessed the combined influence of all factors and comparing the model outcome with base case model (Figure 3.5). The symbols used are conventionally applied: the parallelogram represents manual input, the rectangle indicates process steps, and the diamond signifies decision points.

3.6 Results

In this section, the result discussed how each alternative assumption influenced individually in 3.1 and collectively in 3.2 in compare to the base case model's output. Also, added figures (Figure 3.4 and Figure 3.5), in the figures there are

two parts one is map which used for showing the location of simulated scenarios on the model and the graph showed the spatial variabilities in selected locations.

3.6.1 Sensitivity Analysis of influencing factors:

3.6.1.1 Assumption 1: Soak pit Connections

The size of a building and its distance from the drain could influence whether it becomes a potential soak pit user, thereby affecting the spatial distribution of faecal matter flow. The model was run with two varied conditions the exclusion of faecal flow from 10% larger buildings defined based on their footprint size ($>200\text{m}^2$),

And exclusion of faecal flow from 10% further away buildings ($>30\text{m}$) in Figure 3.4. Building distances from drains are measured using GIS-based proximity analysis to find the pathways from the building centroid (the site of the septic tank). According to the sensitivity analysis, the results show that the exclusion of faecal flow from larger buildings had a greater (27%) reduction on faecal flow than the exclusion of distant buildings (12%).

3.6.1.2 Assumption 2: Septic Tank Emptying

The model was run with only 10% of buildings having emptied septic tanks, utilizing two scenarios: a) a random selection, which is most likely closed to reality, and b) a street cluster approach, (i.e. clustering as a classification technique e.g., selecting buildings according to location on a street (Gil et al., 2012)). The results showed that the random selection approach had a relatively bigger influence (10%) on the faecal mass flow than the street-cluster approach (8%), however, in terms of the spatial pattern, the street-cluster approach had a stronger influence (Figure C- 1) in the appendix. The street cluster scenario is assumed relevant in areas with government buildings, where coordinated emptying practices often make these streets safer by preventing faecal contamination within the neighbourhood. This variability aims to reflect the real-world practices where septic tanks may not be emptied uniformly across an urban area, influenced by logistical, economic, and spatial considerations.

3.6.1.3 Assumption 3: Sludge Transport to Catchment Outlet

Two scenarios were modelled, considering 25% and 75% of faecal mass scraped from two locations. The results show that scraping at the two locations (observation point 1 and 4) and at the two different scraping rates specified reduced faecal mass at the outlet by 5% and 15% respectively (Figure C- 2).

3.6.1.4 Assumption 4: Faecal Matter Production Variability

The model was run with 25% and 75% reduced faecal production from commercial areas. Reductions in faecal matter production in the commercial areas reduced the faecal mass flow at the outlet by 2% and 7% in variants A and B respectively. (Figure C- 3).

3.6.1.5 Assumption 5: Toilet and Septic Tank Availability

The model considered two scenarios: in variant A, excluded 1% and in variant B, excluded 10% randomly selected buildings without toilets. The Results indicated a commensurate change of 1%, and 10% reduction of faecal matter flow at the catchment outlet in line with the percentage of exclusion of the buildings (Figure C- 4).

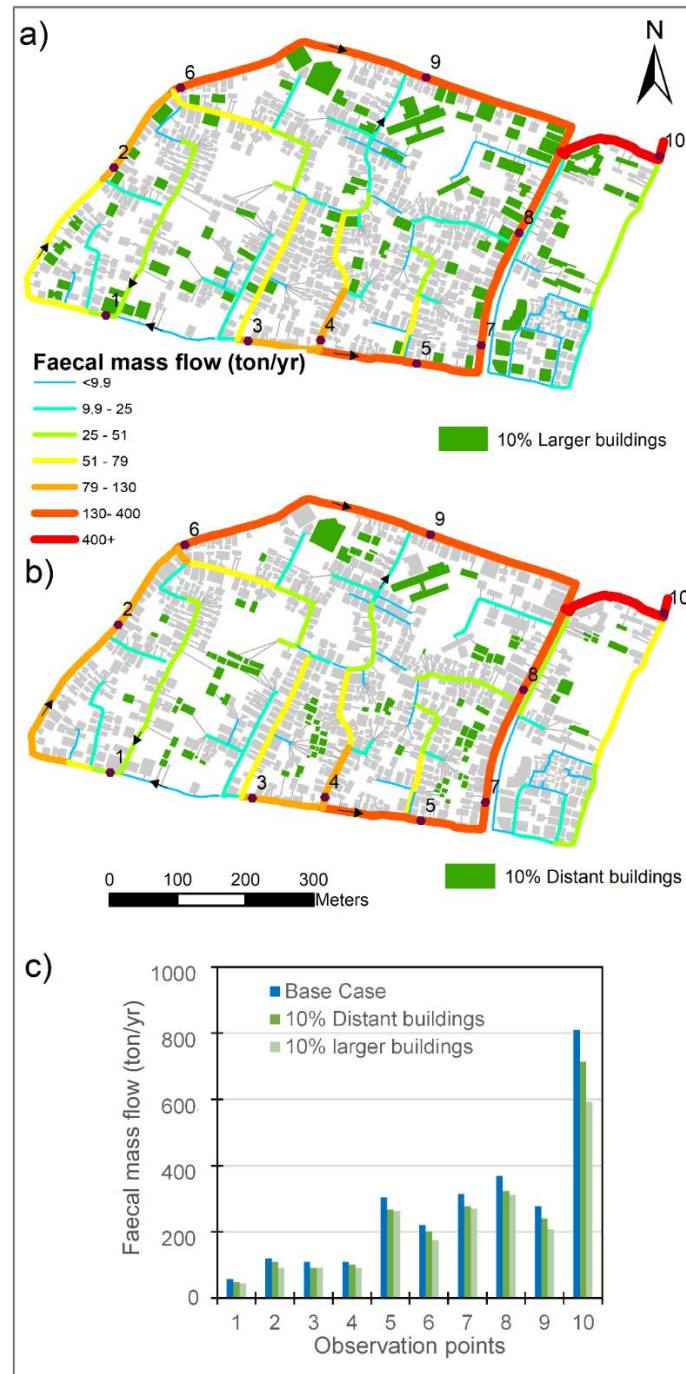


Figure 3.4: Sensitivity analysis and the spatial representation of influencing factor. Here we have shown analysis number 1(A) and 1(B) in Table 3.1. Some septic tanks are connected to soak pits rather than drains considering the alternative assumption with two variants. The maps represented the simulated spatial location of the buildings while the graph showed the spatial variability in 10 selected locations, capping at 400+ to best detail the range seen in most areas. However, 800+ represented the unique conditions at the outlet.

3.6.2 Combined Influencing Factors

The spatial and quantitative analysis of faecal mass flow under varied sanitation management assumptions highlights significant differences in faecal distribution across the model area. The findings are presented through maps and bar charts depicting the faecal mass flow under two distinct scenarios: Variant As and Variant Bs.

3.6.2.1 Most plausible variants combined (As):

The distribution of faecal mass flow under the variant As of alternative assumptions, which are considered more plausible, depicted in the map a) in Figure 3.5.

The characteristics include the presence of soak pits in 10% of larger buildings, the emptying of septic tanks randomly chosen in another 10% buildings, and 1% buildings with no toilets also chosen randomly. Additionally, there are reductions in faecal output from commercial buildings and locations where sludge is actively scraped, marked at 25% respectively. These alternative assumptions have made the faecal flow reduction by 27%, 10%, 5%, 2% and 1% respectively. The difference in faecal mass flow between the most plausible variants and the base-case model is 45%.

The corresponding bar chart (Figure 3.5, b) details the faecal mass flow rates at ten observation points within the catchment area. Compared to the base case, the Variant As assumptions result in significantly decreased faecal mass flow at several points, with the most pronounced difference observed at point 10.

3.6.2.2 Less plausible variants combined (Bs):

Figure 3.5, c provides a map view under the alternative assumptions variant Bs (less plausible) which include more drastic measures such as a 75% reduction in faecal production from commercial buildings and a more aggressive scraping strategy. Additionally, the presence of soak pits in 10% of distant buildings, the emptying of septic tanks in a street chosen in another 10% buildings, and 10% buildings with no toilets also chosen randomly. These alternative assumptions have made the faecal flow reduction by 12%, 8, 15%, 7% and 10% respectively.

The corresponding bar chart (Figure 3.5, d) details the faecal mass flow rates at ten observation points within the catchment area. Compared to the base case, the Variant Bs assumptions result in significantly decreased faecal mass flow at several points, with the most pronounced difference observed at point 7, 9, 6 and 10. In the bar chart shown in Figure d, the comparison of faecal mass flow rates between the base case and Variant Bs reveals diverse impacts across the catchment. The difference in faecal mass flow between the most plausible variants and the base-case model is 52%.

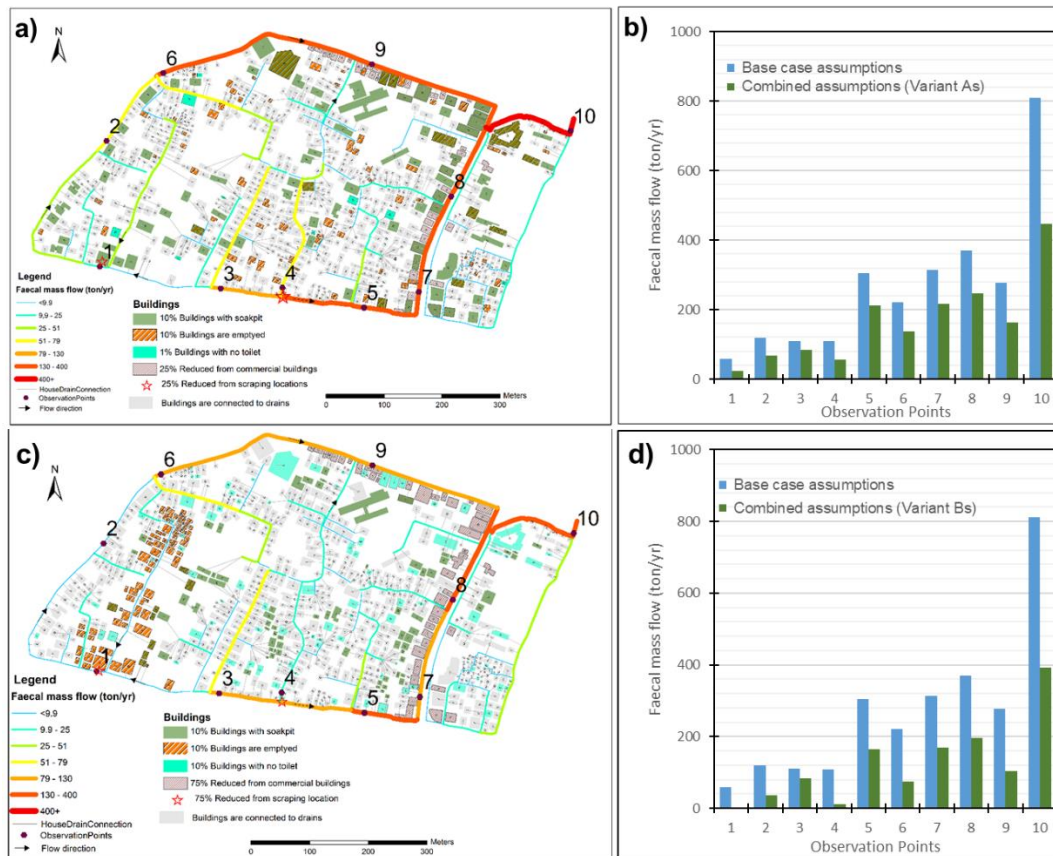


Figure 3.5: The maps provide a spatial and quantitative comparison of two sets of variants, As and Bs, in their distribution and faecal mass flow, with reference to a base case model. Variant As is depicted through the simulation of five factors and their associated faecal mass flows at ten observation points. Variant Bs presents a different set of factors and their flow rates at the same locations. The maps highlight the placement of specific buildings and the variability in faecal flow, in the bar graph it is indicating flow levels up to 400+ to illustrate common conditions, however, 800+ represented the unique conditions at the outlet.

3.7 Discussion

3.7.1 Sanitation Infrastructure and Faecal Mass Flow

In the model, the link between building characteristics and sanitation infrastructure is crucial for understanding patterns of faecal matter distribution. Buildings that manage sewage with soak pits typically prevent faecal matter from entering the local drainage system, thereby reducing overall faecal mass flow. This is exemplified by the observed reductions in faecal flow from larger buildings equipped with soak pits. The strategic emptying of septic tanks, further mitigates the risk of faecal matter entering local drains. Additionally, the commercial aspect of the area is taken into account, potentially because these buildings can contribute significantly high if the public toilet is available or low if it is not available in this perspective assumed low in both maps. Also, buildings lacking toilet facilities are presumably disconnected from the drainage network and finally, considered from some sludge scraped from the drain so it does not contribute to the outlet. These results highlight the importance of appropriate infrastructure and regular maintenance practices in managing urban sanitation effectively.

The map indicates varying levels of faecal mass flow in the drains. The reduced flow rates depend on building density or more effective waste management practices. In both maps the southwest corner shows lower faecal mass flow. While, in figure 3.5, c) is showing a notably lower, this reduced flow rates are indicated by the entire street used emptying services.

3.7.2 Analysis of Influencing factors

The analysis of influencing factors are divided into two sections. The first section assesses the impact of individual factors on faecal matter flow across different scenarios, labelled variant A and variant B, while the second evaluates the collective influence of these factors Table 3.1

The sensitivity analysis of individual factors, such as the presence of soak pits and the septic tank emptying, reveals their varying impacts on the spatial distribution of faecal matter. This analysis is vital for identifying critical areas where interventions might be most needed. For example, larger buildings and

those with regular emptying schedules show a noticeable decrease in faecal flow, highlighting the effectiveness of these practices. By understanding how different factors influence faecal matter movement, urban planners and policymakers can design more targeted and effective sanitation interventions.

Differential Impact of Influencing Factors: In the first analytical section, we examine the specific impacts of Variant A and Variant B. Variant A assesses buildings likely to use soak pits based on their size and usage as government institutions or facilities adhering to building regulations (HBRI, 2015). Variant B considers buildings further from the main drainage system that might employ soak pits for logistical or cost-efficiency reasons, as shown in Figure 3.4. The model tests a 10% septic tank emptying rate across the city using both randomized and cluster selection methods. Cluster selection targets specific areas for faecal matter removal, whereas randomised selection spreads the impact more evenly across the city, as detailed in Figure 3.4 and page 151 (Appendix). This systematic approach evaluates five key factors—soak pit usage, septic tank emptying, faecal matter production by different building types, absence of toilets, and incomplete sludge removal—anticipated to influence the base model outcomes (Figure 3.1).

Collective Influence of Factors: The subsequent section synthesises the effects of all influencing factors, categorized into two groups and illustrated in Figure 3.5. Variant A represents the most plausible scenarios within the city's sanitation framework, while Variant B includes less plausible scenarios. Each group is compared with the base case model (Figure 3.1) to gauge their respective impacts and the broader implications for the city's sanitation services.

The combined analysis of influencing factors brings to light the significant potential for integrated sanitation management practices to reduce faecal matter flow. By implementing a combination of strategies, such as the widespread adoption of soak pits and septic tank emptying, faecal flow can be reduced by as much as 45% to 52% compared to the base case (Figure 3.5). This intense reduction demonstrates the coordinated efforts and supports the concept of a

holistic approach to sanitation management, as detailed in the Sanitation Cityscape framework.

While these factors undoubtedly exist in cities, obtaining evidence during model set up remains challenging. For example, identifying buildings that utilise soak pits would require extensive groundwork. However, estimating their prevalence based on building size and proximity to drains offers a viable starting point. Although this method may not yield perfect predictions, it provides a reasonable approximation of spatial patterns. In this context, the pursuit of absolute proof may not always be feasible or even necessary. Instead, the objective should be to run enough model variants to capture a broad spectrum of potential uncertainties. This can then be followed up with field work if it is considered useful and depending upon the objectives of the model user. This highlights the power of modelling as a tool for navigating uncertainty and generating actionable insights (Peal et al., 2014; Strande et al., 2018).

It is important to recognise that the factors influencing faecal flow interact with one another. For example, if all buildings on a street emptied their septic tanks, the necessity for drain scraping could be eliminated, as the drains would not receive any faecal matter (Figure 3.5c). Our analysis of various scenarios (Figure 3.5) showed that different sanitation management practices have a combined influence, leading to a 50% reduction in faecal flow at the outlet (observation point 10). These results align with the citywide approach proposed by Scott & Cotton (2020), who advocate for a holistic understanding of sanitation service delivery through their Sanitation Cityscape framework. By quantifying how the combined effect of various management practises can affect sanitation outcomes at a spatial level, our work will enhance the Sanitation Cityscape model and City Wide Inclusive Sanitation (CWIS) and add empirical evidence to the qualitative frameworks discussed in both Scott & Cotton (2020) and Lüthi et al. (2020).

3.7.3 Challenges and Practical Implications:

Finding buildings that have soak pits requires extensive fieldwork. A functional way to identify their existence is to take into account the building's size and the proximity to drainage systems. This method provides a reasonable estimate of

spatial distributions, although not produce perfect predictions. More fieldwork is necessary for precise validation, but this approach is consistent with earlier studies and advances our knowledge of faecal flow patterns in urban settings.

(Rodriguez et al., 2020; Roldin et al., 2012). The factors influencing spatial pattern of faecal flow significantly. For instance, if all buildings on a street emptied their septic tanks, it could eliminate the need for drain scraping. Our analysis shows that combined sanitation management practices can lead to a ~50% reduction in faecal flow. The study offers new perspectives on the interplay of various factors that shape spatial patterns faecal matter flow in the city (Foster et al., 2021; Peal et al., 2020). The results support a holistic approach to sanitation, which aligns with the Sanitation Cityscape framework and City Wide Inclusive Sanitation (CWIS), enhancing both theoretical models and empirical evidence of effective urban sanitation management. This method emphasises the utility of modelling as a tool for managing uncertainty and informing practical interventions, especially in resource-constrained urban settings. Moreover, the importance of our study becomes clearer when we look at the WHO-UNICEF recommendations (UNICEF/WHO, 2023). Their guidelines draw attention to the limits of current sanitation practices in reducing faecal contamination across the sanitation chain.

3.7.4 Limitations of this work and the future need

Urban sanitation systems are highly complex, and modelling these systems poses significant challenges. Technical limitations often constrain the precision of simulations, while budgetary constraints may restrict the scope of data collection efforts (Strande et al., 2018,). Additionally, the availability and quality of data in unsewered urban areas frequently impede comprehensive analysis. Despite these obstacles, our study has made methodological choices that attempted to balance practicality with the need for actionable insights. These choices include the simulation of varying scenarios based on plausible and less plausible variants, which helps to understand the potential impacts of different sanitation management strategies under varied urban conditions.

While our model provides valuable insights, it is essential to acknowledge its limitations. The assumptions necessary for modelling, due to partial data,

introduce uncertainties that could affect the generalizability of the results (Saltelli et al., 2020). These limitations highlight the ongoing need for fieldwork to check the reliability of the model and gather insight data of the city, which can improve the usefulness of sanitation models.

Future research avenues should explore the sensitivity of different percentages and spatial variants, particularly for buildings with soak pits. Moreover, other factors like GPS location, building area, and design warrant investigation for their potential impact on faecal production (Niwagaba et al., 2014).

Additionally, financial and time constraints necessitated the use of indicative variants in our model. While this approach captures essential spatial patterns, it also introduces a level of uncertainty. By continuing to refine these models and validate their assumptions through empirical research, we can enhance their utility in planning and implementing effective sanitation strategies.

3.8 Conclusions

The study identifies five major influencing factors: septic tank emptying, soak pit usage, sludge removal from drains, faecal matter production variations by building type, and toilet availability. The sensitivity of the model to the assumptions underpinning these influencing factors was then assessed through an uncertainty analysis of impact on the spatial pattern of faecal flow. The most significant findings indicate that the exclusion of larger buildings (as defined on page 78) reduce faecal flow by 27%, while the exclusion of distant buildings (as defined on the same page) reduce it by 12%. A random spatial pattern of septic tank emptying reduces faecal mass flow by 10%, whereas a street-clustered pattern of emptying reduces it by 8%. Also, by scraping 25% in variant A and 75% in variant B of the faecal mass from selected areas (observation point 1 and 4) reduces faecal mass flow at the sub-catchment outlet by 5% and 15% respectively. Furthermore, the exclusion of 25% and 75% reductions in faecal production from buildings identified as being commercial (and therefore with a lower resident population) reduces faecal mass flow at the outlet by 2% and 7%, respectively. In addition, 1%, and 10% reduction of faecal matter flow simulated

the absence of toilet in randomly selected buildings in the sub catchment. Coincidentally, the influence at the outlet is similarly 1% and 10% respectively.

The comparative analysis of individual factors across two variants have revealed that the combined impact of these factors can change the faecal flow by approximately 50%, while individually these factors may appear to have a negligible impact; however, simulated sensitivity analysis reveals that collectively this finding reinforces the need for a more advanced, spatially informed approach to sanitation management in unsewered cities. This study addresses the challenges of modelling faecal matter flow in unsewered urban settings—a crucial component of effective urban sanitation management. Our innovative methodology incorporates open-source data and GIS technology, demonstrating the feasibility and necessity of spatial representation and understanding of influencing factors in this context.

This research offers a foundational understanding of the complex spatial dynamics of faecal matter movement in unsewered urban settings, serving as an important milestone toward a potential future where effective, proactive, and data-informed sanitation management could be achievable. Future research could focus on validating and scaling this methodology, taking into account the unique spatial characteristics of different urban environments. Such adaptability would enable a transition from reactive to proactive sanitation management strategies. In this context, a 'reactive' approach would typically involve addressing sanitation issues as they arise, often leading to temporary and fragmented solutions. In contrast, a 'proactive' approach would anticipate future challenges, enabling more comprehensive and long-term planning.

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References

- Alam, M.-U., Sharior, F., Ferdous, S., Ahsan, A., Ahmed, T., Afrin, A., Sarker, S., Akand, F., Archie, R. J., Hasan, K., Renouf, R., Drabble, S., Norman, G., Rahman, M., & Tidwell, J. B. (2020). Strategies to Connect Low-Income Communities with the Proposed Sewerage Network of the Dhaka Sanitation Improvement Project, Bangladesh: A Qualitative Assessment of the Perspectives of Stakeholders. *International Journal of Environmental Research and Public Health*, 17(19), 7201. <https://doi.org/10.3390/ijerph17197201>
- Amin, N., Liu, P., Foster, T., Rahman, M., Miah, M. R., Ahmed, G. B., Kabir, M., Raj, S., Moe, C. L., & Willetts, J. (2020). Pathogen flows from on-site sanitation systems in low-income urban neighborhoods, Dhaka: A quantitative environmental assessment. *International Journal of Hygiene and Environmental Health*, 230, 113619. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113619>
- Bari, M. N. (2017). Study on Existing Faecal Sludge Management Situation in Rajshahi City. *Proceedings of the WasteSafe 2017 – 5th International Conference on Solid Waste Management in South Asian Countries 25-27 February 2017, Khulna, Bangladesh STUDY, March*.
- Bari, N., Bushra, A., & Zaman, J. (2018). Management of faecal sludge by rajshahi city corporation. *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development, July*, 1–11. http://www.iccesd.com/proc_2018/Papers/r_p4803.pdf
- Blackett, I., Hawkins, P., & Heymans, C. (2014). *The Missing Link in Sanitation Service Delivery: A Review of Fecal Sludge Management in 12 Cities*. <https://doi.org/10.13140/RG.2.1.4072.7205>
- Bustos, M. F. A., Hall, O., Niedomysl, T., & Ernstson, U. (2020). A pixel level evaluation of five multitemporal global gridded population datasets: a case study in Sweden, 1990–2015. *Population and Environment*, 42(2), 255–277. <https://doi.org/10.1007/s11111-020-00360-8>

- Foster, T., Falletta, J., Amin, N., Rahman, M., Liu, P., Raj, S., Mills, F., Petterson, S., Norman, G., Moe, C., & Willetts, J. (2021). Modelling faecal pathogen flows and health risks in urban Bangladesh: Implications for sanitation decision making. *International Journal of Hygiene and Environmental Health*, 233, 113669. <https://doi.org/10.1016/j.ijheh.2020.113669>
- Gil, J., Beirão, J. N., Montenegro, N., & Duarte, J. P. (2012). On the discovery of urban typologies: Data mining the many dimensions of urban form. *Urban Morphology*, 16(1), 27–40. <https://doi.org/10.51347/jum.v16i1.3966>
- HBRI. (2015). *Bangladesh National Building Code*.
- Koné, D. (2010). Making urban excreta and wastewater management contribute to cities' economic development: a paradigm shift. *Water Policy*, 12(4), 602–610. <https://doi.org/10.2166/wp.2010.122>
- Leidig, M., Teeuw, R. M., & Gibson, A. D. (2016). Data poverty: A global evaluation for 2009 to 2013 - implications for sustainable development and disaster risk reduction. *International Journal of Applied Earth Observation and Geoinformation*, 50, 1–9. <https://doi.org/10.1016/j.jag.2016.03.001>
- Leong, W. K., Ngo, A. L. K., Wong, A. C. H., Ling, J. H., & Sia, H. T. (2022). The Mandatory 4 Years Desludging Frequency of Underground Septic Tanks in Residential Areas: A Case Study in Sibu Sarawak, East Malaysia. *Journal of the Civil Engineering Forum*, 8(2 SE-Articles). <https://doi.org/10.22146/jcef.3812>
- Lüthi, C., Willetts, J., & Hoffmann, S. (2020). Editorial: City-Wide Sanitation: The Urban Sustainability Challenge. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.585418>
- Mehta, M., Mehta, D., & Yadav, U. (2019). Citywide Inclusive Sanitation Through Scheduled Desludging Services: Emerging Experience From India. *Frontiers in Environmental Science*, 7. <https://doi.org/10.3389/fenvs.2019.00188>
- Mills, F., Willetts, J., Petterson, S., Mitchell, C., & Norman, G. (2018). Faecal

- pathogen flows and their public health risks in urban environments: A proposed approach to inform sanitation planning. *International Journal of Environmental Research and Public Health*, 15(2). <https://doi.org/10.3390/ijerph15020181>
- Müller, A., Österlund, H., Marsalek, J., & Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. *Science of The Total Environment*, 709, 136125. <https://doi.org/10.1016/j.scitotenv.2019.136125>
- Niwagaba, C. B., Mbéguéré, M., & Strande, L. (2014). Faecal Sludge Quantification, Characterisation and Treatment Objectives. In L. Strande, M. Ronteltap, & D. Brdjanovic (Eds.), *Faecal Sludge Management Systems Approach for Implementation and Operation* (pp. 19–44). IWA Publishing.
- OpenStreetMap Contributors. (2019). Planet.osm. <https://planet.openstreetmap.org/>
- Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., Schoebitz, L., Scott, R., Sleigh, A., Strande, L., & Veses, O. (2020). Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned From a Global Implementation of Excreta-Flow Diagrams. *Frontiers in Environmental Science*, 8, 1. <https://doi.org/10.3389/fenvs.2020.00001>
- Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2014). Fecal sludge management (FSM): analytical tools for assessing FSM in cities. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 371–383. <https://doi.org/10.2166/washdev.2014.139>
- Quang, C. N. X., Giang, N. N. H., Hoa, H. V., & Hung, P. Q. (2022). Effects of sediment deposit on the hydraulic performance of the urban stormwater drainage system. *IOP Conference Series: Earth and Environmental Science*, 964(1), 12020. <https://doi.org/10.1088/1755-1315/964/1/012020>
- Raj, S. J., Wang, Y., Yakubu, H., Robb, K., Siesel, C., Green, J., Kirby, A., Mairinger, W., Michiel, J., Null, C., Perez, E., Roguski, K., & Moe, C. L.

- (2020). The SaniPath Exposure Assessment Tool: A quantitative approach for assessing exposure to fecal contamination through multiple pathways in low resource urban settlements. *PLoS ONE*, 15(6), 1–18. <https://doi.org/10.1371/journal.pone.0234364>
- Rodriguez, F., Le Delliou, A.-L., Andrieu, H., & Gironás, J. (2020). Groundwater Contribution to Sewer Network Baseflow in an Urban Catchment-Case Study of Pin Sec Catchment, Nantes, France. In *Water* (Vol. 12, Issue 3). <https://doi.org/10.3390/w12030689>
- Roldin, M., Fryd, O., Jeppesen, J., Mark, O., Binning, P. J., Mikkelsen, P. S., & Jensen, M. B. (2012). Modelling the impact of soakaway retrofits on combined sewage overflows in a 3km² urban catchment in Copenhagen, Denmark. *Journal of Hydrology*, 452–453, 64–75. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2012.05.027>
- Rose, A. N., McKee, J. J., Sims, K. M., Bright, E. A., Reith, A. E., & Urban, M. L. (2020). *LandScan 2019* (2019 RI-). Oak Ridge National Laboratory SE - July 1, 2020. <https://landscan.ornl.gov/>
- Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Espeland, W., Kay, J., Lo Piano, S., Mayo, D., Jr, R., Portaluri, T., Porter, T., Puy, A., Rafols, I., Ravetz, J., Reinert, E., Sarewitz, D., Stark, P., & Vineis, P. (2020). Five ways to ensure that models serve society: a manifesto. *Nature*, 582, 482–484. <https://doi.org/10.1038/d41586-020-01812-9>
- Scott, P., & Cotton, A. P. (2020). The Sanitation Cityscape – Toward a Conceptual Framework for Integrated and Citywide Urban Sanitation. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00070>
- Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B. J., & Niwagaba, C. B. (2018). Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions. *Journal of Environmental Management*, 223(June), 898–907. <https://doi.org/10.1016/j.jenvman.2018.06.100>

- Sultana, M. S., Waine, T., Bari, N., & Tyrrel, S. (2023). Towards a new spatial representation of faecal sources and pathways in unsewered urban catchments using open-source data. *Journal of Water, Sanitation and Hygiene for Development*, 13(4), 289–300. <https://doi.org/10.2166/washdev.2023.227>
- Tabassum, S. (2020). Drainage system, its water quality and health effect: A case study of Rajshahi city, Bangladesh. *Scientific Journal of Environmental Sciences*, 9(1), 323–336. <https://doi.org/10.14196/sjes.v9i1.2612>
- UNICEF/WHO. (2023). *Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender*. United Nations Children's Fund (UNICEF) and World Health Organization (WHO). https://washdata.org/sites/default/files/2022-01/jmp-2021-wash-households_3.pdf
- WaterAid. (2018). *SFD Lite Report of Rajshahi City Corporation Bangladesh*.

4 ASSESSING THE RELIABILITY AND UTILITY OF OPEN-SOURCE DATA USED FOR SPATIAL SCALE CHARACTERISATION OF URBAN SANITATION INFRASTRUCTURE - A FIELD STUDY IN RAJSHAHI, BANGLADESH⁴

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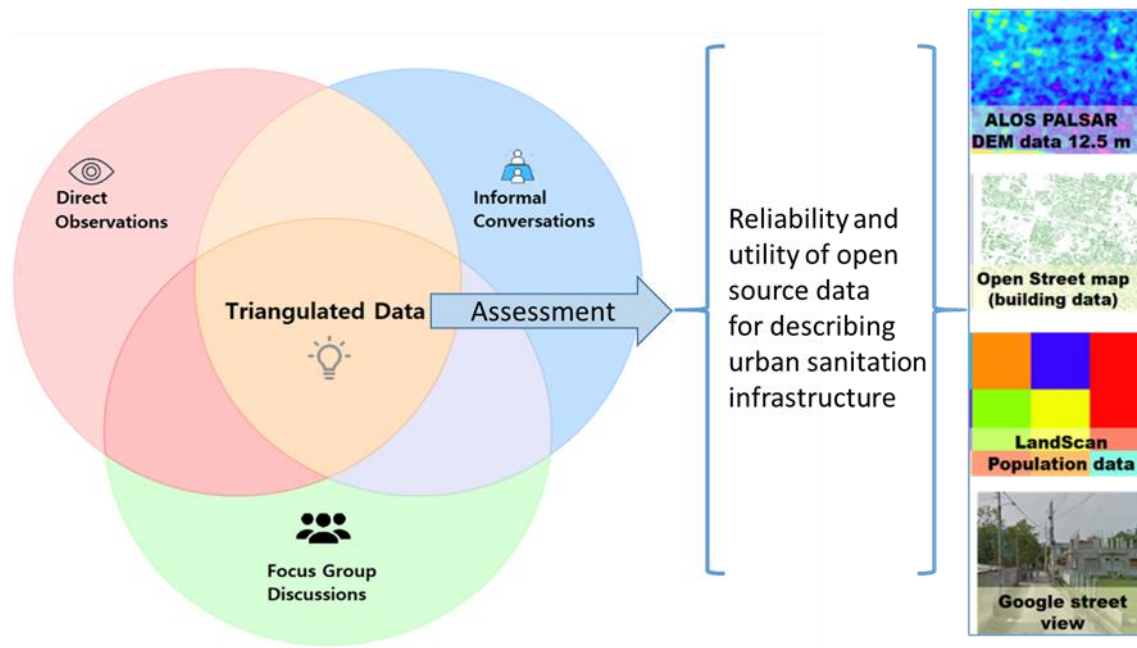
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4.1 Highlights:

- The study assesses the reliability of using open-source data in modelling faecal matter flow in unsewered cities.
- Fieldwork in Rajshahi combines observations, conversations, and group discussions to understand sanitation infrastructure.
- There is 80% consistency between modelled flow direction and field observations, validating open-source data usage.
- The research reveals a lack of proactive sanitation management.

⁴ Part of this chapter was presented at a conference at Cranfield University: Sultana MS, Waine T, Bari N, Tyrrel S (2022), Field calibration of an open-source data derived spatial representation of unsewered urban sanitation in Bangladesh. Oral, Early Career People in Water Conference at Cranfield University, 16-17 November 2022

4.2 Graphical Abstract



4.3 Abstract

This research aims to evaluate the effectiveness of open-source data for modelling the sources and movement pathways of faecal matter in unsewered urban areas, with a focus on the complex spatial aspects of sanitation management, particularly secondary cities. Utilising a triangulated methodological approach that includes direct observations, informal conversations, and focus group discussions, the study explores the reliability of using open-source data to map the sources and movement of faecal matter. It also seeks to gain insights into the sanitation infrastructure and management practices in Rajshahi, a secondary city in Bangladesh. The findings demonstrate an 80% alignment between the model's simulated flow directions and actual field observations, highlighting the potential of using open-source data in urban catchments. The study further uncovers that 80% of buildings have a connection to storm drains. Many of these connections allowed faecal matter to overflow from septic tank into drains. Despite the efforts of the City Corporation, which maintains a team for managing the drainage system through activities like drain scraping and unblocking, blocked and overflowing drains remain a common

issue, particularly during the rainy season. Informal conversations reveal an absence of proactive maintenance, or monitoring sanitation services, and focus group discussions point to a widespread unawareness of existing sanitation management system. Additionally, sanitation maintenance, including drain upkeep, is predominantly reactive, addressing issues only as they arise. Integrating knowledge from field studies with the use of open-source data, supports a more proactive and informed approach to urban sanitation management. This can provide a more data-driven approach that directly supports of addressing complex sanitation issues in secondary cities. The insights from this study advocate for a more proactive and informed approach to sanitation management in similar settings, aiming to enhance public health and quality of life.

4.4 Introduction

Sanitation management poses significant challenges, often necessitating a spatial perspective because faecal solids, wastewater and urban runoff move in city-scale networks. This need becomes increasingly critical with rising urbanization and population pressures, demanding a more comprehensive attention to the spatial variability of sanitation systems. The release of faecal matter from septic tanks into storm drainage is a widely known health hazard in urban areas (Ekklesia et al., 2015; Mills et al., 2018; Sercu et al., 2011). Despite the opportunities presented by recent advances in geospatial data and satellite remote sensing, their application in the sanitation sector, remains largely underexplored (Leidig et al., 2016). In the past decade, numerous innovative methodologies have been developed to assess faecal matter production and its fate in urban settings (Foster et al., 2021; Peal et al., 2020; Strande et al., 2018). Among these methods, the Shit Flow Diagram (SFD) has proven particularly beneficial, providing an aggregate assessment of the entire city (Peal et al., 2014). However, a more spatially distributed approach was adopted by Sultana et al. (2023) where open-source data has been utilised to spatially represent sanitation systems in a specific area of Rajshahi city, Bangladesh. This novel

approach has suggested new insights into faecal production sources and faecal movement pathways at an urban sub-catchment scale.

Regardless of these advances, there is a lack of knowledge about the reliability of using open-source data for planning sanitation systems. Questions about the quality of data and completeness persist, especially regarding its capability to accurately represent the complexities of diverse and individually managed sanitation systems connected to urban drainage networks (Amin et al., 2020). To address these uncertainties, research by Sultana et al., (in prep. Chapter 3) analysed several key assumptions and identified five key influencing factors that impact the understanding of spatial patterns of faecal matter movement. These are the emptying of septic tanks, the use of soak pits, and sludge removal from drains, variations in faecal matter production by building types, and the presence or absence of toilets. However, the research used several plausible scenarios to assess the impact of influencing factors in the simulation without any field data. Fieldwork is essential to provide additional data, which can be used to refine the model. It is yet to be established whether fieldwork can provide additional clues, which can subsequently be used to improve the methodology. Comprehensive house-to-house surveys, though beneficial, are often unaffordable for municipal authorities. This research explores the use of open-source data supplemented with limited field observation as a potential solution for effective faecal sludge management in unsewered cities.

This research aims to identify potential enhancements to the methodology for spatial faecal mass flow mapping, assess the validity of assumptions and where possible the model outputs in the test catchment, and deepen our understanding of the sanitation landscape in Rajshahi city. This integrated approach is necessitated by the current low confidence in existing sanitation data, the preliminary nature of a prototype model reliant on limited and untested data, and the imperative to establish the reliability and utility of this innovative mapping method.

4.5 Study area

This research focuses on Rajshahi, one of the largest secondary cities in Bangladesh. Rajshahi is primarily divided into two hydrological catchments. The study specifically targets the western catchment, drawing on a detailed model from the work of Sultana et al., 2023. The western catchment of Rajshahi is where topography and hydrological dynamics are intricately related, with surface water flow largely dictated by a south-to-north gradient, directing precipitation and wastewater towards the Baranai River and the beels to the north of the city (Clemett et al., 2006). The streams, together with the engineered storm drains, form a structured hierarchy that plays a critical role in the area's drainage system. Each major stream, several of which have undergone engineering modifications, creates its own series of sub-catchments. One such sub-catchment was previously modelled (Figure 4.1). Sanitation within this catchment is characterised by the absence of a centralized sewerage system, as is the case in other parts of the city, leading to a reliance on individual septic tanks connected to street drains. This is complicated by the significant proportion of systems that do not adhere to the national building code, with many releasing wastewater, along with escaped faecal matter, into this drainage system.

The area is a mix of residential and commercial zones. Commercial buildings, predominantly small shopping complexes, hospitals, and diagnostic centres, are mainly found in the northern and eastern edges of the model area.

Field observations were primarily conducted within the designated model area, with a few strategically chosen locations outside, within the wider western catchments (Figure 4.1). This approach was essential for evaluating and contrasting sanitation infrastructure across broader regions, crucial for enhancing the model for larger catchments or cities.

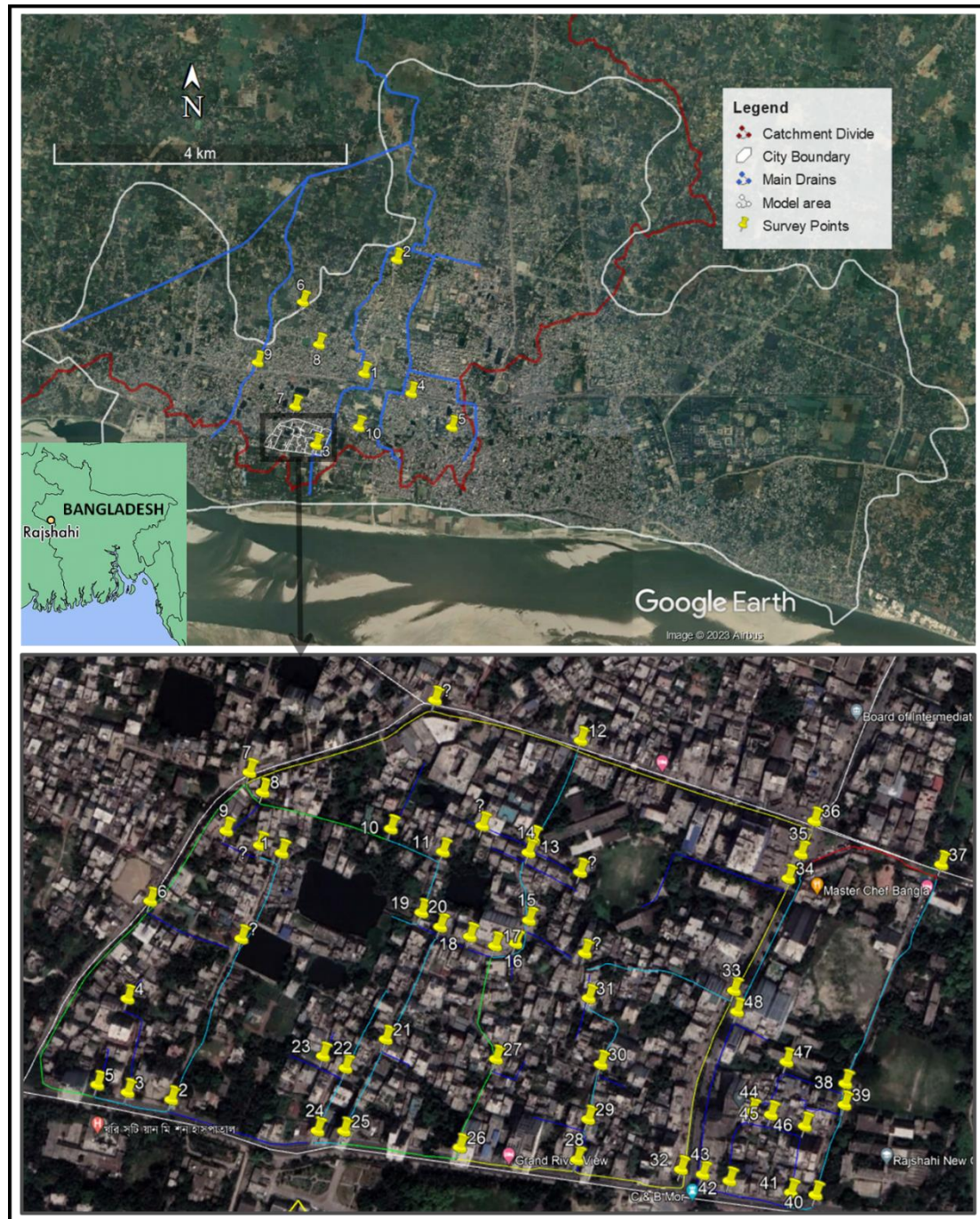


Figure 4.1: The study area within Rajshahi city, capturing the western catchment and major hydrological features in a comprehensive aerial view. The Google Earth image of Rajshahi city at the top, shows the city boundary, catchment divide line, main drains of the western catchment and prototype model area. It also shows the survey location points. The map shows the detailed model area and the 48 drain connection points used as direct observation locations.

Furthermore, focus group discussions took place outside the model area to check the sanitation infrastructural similarities within the city. This strategy was crucial for capturing a wide range of viewpoints, essential for understanding diverse experiences and challenges related to sanitation in Rajshahi. Including data from various areas of the city ensures a comprehensive and balanced view of the sanitation issues, considering the variety in experiences and perspectives. The city corporation office, vital to this research, is also located outside the model area.

4.6 Methods

This study employs a wide-ranging methodology to investigate the sanitation infrastructure in Rajshahi, combining various approaches over a three-week fieldwork period from 3 August to 25 August 2022. Figure 4.2 illustrates this methodology, which includes direct observations, informal conversations, and focus group discussions. The weather during this period was mainly dry and humid, with occasional rainy conditions.

The method gathers both quantitative data on sanitation facilities and qualitative insights into faecal management practices. By incorporating observations, the study tests the validity of the open-source data model. Additionally, informal conversations and focus group discussions provide vital context, revealing the factors that influence spatial variability and the movement of faecal matter within the city. The reliability of the methodology is assessed systematically, with a focus on its practical use in the context of open-source data for spatial analysis. The following sections provide detailed elaboration on each of these methodological aspects.

4.6.1 Direct observation

Direct observation was the most important part of this field study to understand the sanitation context and check the reliability of the model. Data collection was carried out using a pre-prepared Google Form with set of questions to check the model's reliability and understanding sanitation infrastructure and management

system that was also, complemented by traditional note-taking (Table 4.1). All the responses are made available in the supplementary information.

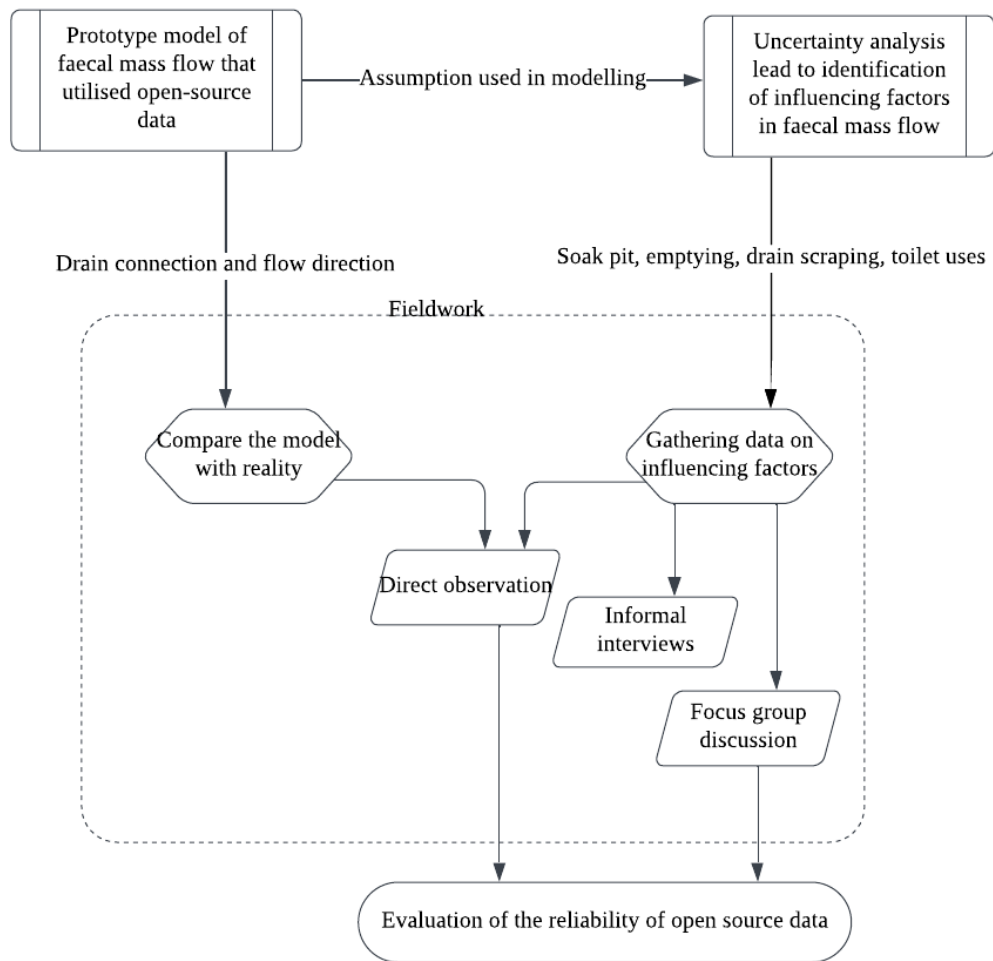


Figure 4.2: Methodological Flowchart outlining the integrated approach of the study, encompassing direct observations, informal conversations, and focus group discussions. This chart visualises the sequence and interplay of the methods used. The symbols are conventionally applied: the rectangle represents a predefined process, the parallelogram represents data collection, the hexagon indicates preparation steps, and the oval signifies a terminator or end point.

Table 4.1: The direct observation questionnaire was designed to assess the model reliability and the presence of influencing factors, also, to understand the sanitation infrastructure. This was carried out at 58 sampling locations.

Observation Items	Response Options	Definition	Rationale
Station ID	Numeric	Unique identification of the location.	Provides a spatial reference for data analysis.
Latitude and longitude	Numeric	Coordinates marking the precise location.	Facilitates spatial analysis and integration with Geographic Information Systems (GIS) tools.
Flow direction	North / South / East / West / Other	Direction of faecal mass (wastewater) flow in the drain.	Validates model-predicted flow directions against observed directions, to assess model accuracy.
Drain to drain connection	Yes / No	Whether the drain is connected to the broader drainage network.	Indicates potential pathways for faecal mass flow within the drainage system.
Width of the drain	Numeric	The measurement of the width of the drains.	Assists in understanding the capacity of the drains and identifying potential bottlenecks within the flow system and the reliability of the drainage map itself.
Drain cover	Yes / No / Partly	Status of the drain cover.	Affects accessibility and observation.
Visible connection (building and drain)	Yes / No	Whether a connection between buildings and the drainage system is observable.	Validates assumptions about the connectivity of drains allowing assessment of model accuracy.
Visible faecal matter in the drain	Yes / No	Presence of faecal matter visible in the drain.	A visual assessment of the nature of septic tank overflow.

Signs of overflow from the drain	Yes / No	Evidence of overflow occurring from the drain.	Indicates capacity issues or blockages downstream, relevant for assessing overflow events and their potential for environmental and health impact.
Scraped material present	Yes / No	Observation of desludged material on the sides of the drain.	Provides insights into maintenance practices and blockage locations, indicating recent cleaning efforts.
Water logging	Yes / No	Presence of water in the drain without noticeable flow.	Signals areas of stagnant water due to sludge and other solid waste materials, hinting at ineffective drainage and potential health hazards.
Complete blockage due to sludge	Yes / No	The drain is completely blocked with sludge and solid waste.	Serves as a direct indicator of drain functionality, reflecting severe challenges in sanitation infrastructure.
Accumulation of solid waste	Yes / No	The drain is mostly filled with solid waste.	Highlights issues with waste management, affecting drainage efficiency and environmental health.
Comments	Text entry	Facilitates the capture of qualitative insights and anomalies not directly addressed by the checklist.	

One of the main goals was to observe faecal sources and movement pathways through the hierarchical drainage system. According to the drainage master plan of Rajshahi city, there are three types of drains which are classified on the basis of their width. These are identified as primary, secondary, and tertiary drains. Primary drains are the main drain in the area, serving as the principal conduits in the locality, possess a width exceeding a metre. Secondary drains are medium-type drains connected to the primary drain and tertiary drain, with a width of less than a metre and more than half metre. Tertiary drains have a width of less than half a metre. They are the smallest type of drain, responsible for carrying wastewater away from buildings to secondary drains, which then connect to primary drains (Islam et al., 2021; Tabassum, 2020).

Some buildings also had direct connections to secondary and primary drains when situated adjacently (Figure 4.3). The technique used in this approach was to observe and document the drainage system in relation to the flow direction. To do this, 48 drainage junction points (where two or more drains are joined) were identified, where building-drain connection, flow direction and sign of faecal matter accumulation, as well as a few other sanitation features were checked (Figure 4.1). For instance, questions like "Is there any visible connection to a building/septic-tank and drain?" were designed to explore the assumptions used in the modelling (Sultana et al., 2023) - whether all septic tanks are connected to the drains. Observations were made at each location, focusing on buildings adjacent to the sampling points. Multiple buildings were observed at each junction i.e., sampling point but recorded as one observation (Table 4.1). Let us take the example of a building-to-drain connection. If I observed three buildings and two of them had visible pipes connecting to the drain, that point was logged as 'yes', implying that the majority of the buildings in that area were connected to the drain. Finally, the percentage of sampling points with a visible building to drain connection was calculated as the number of sampling points logged as 'yes' as a percentage of the total sampling point number (n=58).

To assess the consistency of the above findings across larger areas, 10 additional points around the western catchment were identified (Figure 4.1). In this case, the sampling points were selected focusing on the primary drains and their connection with other drains (Figure 4.3). Similar to the aforementioned sub-catchment level observation, GPS positions were taken at these points, and infrastructure within 100 - 200m of each point was investigated instead of investigating few building-to-drain connection, recording similar sanitation aspects as before (Table 4.1).



Figure 4.3: The primary drain has a width of more than 1 metre within the area which receives the flow from secondary drains (less than a metre in width) which in turn receive flow from tertiary drains of a width of less than half a metre.

4.6.2 Informal conversations and dialogue

Fieldwork was integral to our study, consisting of direct observations and complemented by purposeful conversations with local residents, as well as structured discussions with sanitation professionals. A comprehensive view of the sanitation landscape was provided by sanitation professionals, identified through our local partners and selected for their direct or indirect roles in the sanitation governance of the city. Consultations with an academic from a local university, three city authority staff members, and four sanitation professionals yielded in-depth knowledge on various aspects of sanitation management. Scheduled meetings acted as platforms for sharing research findings and discussing the practical challenges of sanitation management, from septic tank emptying practices to the maintenance of storm drains. To guide these expert discussions, we utilised a checklist (Figure 4.4) that focused on crucial aspects of sanitation

management, such as toilet availability, soak pit usage, drain scraping procedures, and commercial toilet policies.

Additionally, informal conversations with local residents occurred during the direct observations. Engaging with nearby or interested locals, we gained a deeper understanding of the reality on the ground. The informal yet targeted conversations revealed critical details about sanitation, such as drain continuity, building drain connectivity, overflow incidents, and cleaning routines. These dialogues not only enhanced our field observations but also were instrumental in creating a nuanced understanding of the sanitation facilities.



Figure 4.4: Check list for informal conversations with the sanitation professionals on data availability of influencing factors of faecal matter flow and understanding the sanitation management system of the city.

4.6.3 Focus group discussion

Extending beyond the realm of informal conversation and interviews, the implementation of a focus group discussion was undertaken to check the reliability of the assumptions e.g., septic tank connection to the drain, and to understand the context of sanitation systems from the perspective of the users. A customised checklist aligning with the aforementioned check list (Figure 4.4) was followed here (Figure 4.5). The group discussion took place in an older part of the city that was not a slum but was highly populated and housed people with low incomes.

The focus group discussion was facilitated in collaboration with the local partner. The focus group encompassed twelve local women, who are the members of The Livelihoods Improvement of the Urban Poor (LIUPC) Project, from low-income families. Prior to the discussion, the researcher obtained the participants' consent, clarified the research goals, and ensured understanding of the subsequent use of the data collected. A pre-determined checklist (Figure 4.5) was used to guide the discussions, ensuring the collection of information and enabling participants to share their experiences and insights on the topic. Topics on the checklist included, building-drain connectivity, incidents of overflow, occurrences of flooding, and cleaning frequency, amongst others. The participants were encouraged to share their experiences and knowledge on various topics, including environmental pollution.

1 Understanding of Sanitation Systems	
Can you tell us what you know about where the waste goes after it leaves your home?	Why do you think it's important to manage waste?
2 Observations of Septic Tank and Drain Connectivity:	
Have you noticed if the septic tanks are connected to the drains in your area?	What do you think happens when the septic tank gets full?
3 Use of Sanitation Services:	
Have you or someone you know used a service to empty the septic tank? If not, how is it usually managed?	Can you recall any time when you saw a truck emptying waste in your area?
4 Experiences with Drainage Overflow:	
How often do you experience overflow from the drains, especially when it rains?	Can you describe what happens in your area when there's a heavy rain?
5 Encounters with Flooding and Faecal Matter Visibility:	
Have you ever seen faecal matter during or after floods?	What are your feelings about flooding and its impact on your community?
6 Drain Sludge Management:	
Have you seen how drain sludge is handled in your area?	What happens to the sludge after it's removed from the drain?
7 Insights on Environmental Pollution and Health:	
Do you think there is a connection between health and how clean your environment is?	How does the pollution from waste affect you and your family?

Figure 4.5: Check list for focus group discussions. Topics on the checklist included, building-drain connectivity, incidents of overflow, occurrences of flooding, and cleaning frequency, amongst others.

4.7 Results and Interpretation

The outcomes of this study, presented here, are designed to meet the research aim: assessing the validity of model assumptions and outputs, and improving the methodology for spatial faecal matter flow mapping and enhancing the understanding sanitation context of Rajshahi city. These findings are broadly categorised into direct observations, informal interviews, and focus group discussions. The integrated findings from the field investigation were presented in Table 4.2 and described in relation to the aim of the study in discussion section. The direct observations substantiate parameters of the model through physical inspections and local interactions in the prototype area and wider catchments. The interviews and focus group discussions further evaluate the insight of sanitation management practices and data availability of influencing factors of faecal matter flow, and understanding sanitation system of Rajshahi.

4.7.1 Direct observation

In the city, the majority of the buildings use septic tanks and these are connected to the drain for the wastewater management. The survey result (Figure 4.6) showed around 80% buildings are connected to drains based on 58 sampling location. It is also observed that while most drains are covered, primary drains are usually not. The results showed that around 50% of the drains were completely covered with concrete slabs, with the rest being either partially covered with the same material or not covered at all. All drains, covered or uncovered, are hydraulically open channel i.e., flow is gravity driven (Li et al., 2020). Flow directions and water in these drains can be seen directly even if they are covered since they have manholes for maintenance and the manhole lid has multiple small lock holes, large enough, to show the water within and its flow. It was also observed that some drains, mostly secondary ones, backed up when it rained, while some (~ 5%) tertiary drains were found to be blocked with the solid waste like cans, plastic bags, paper carton box and sludge-like sediment of uncertain composition or origin.

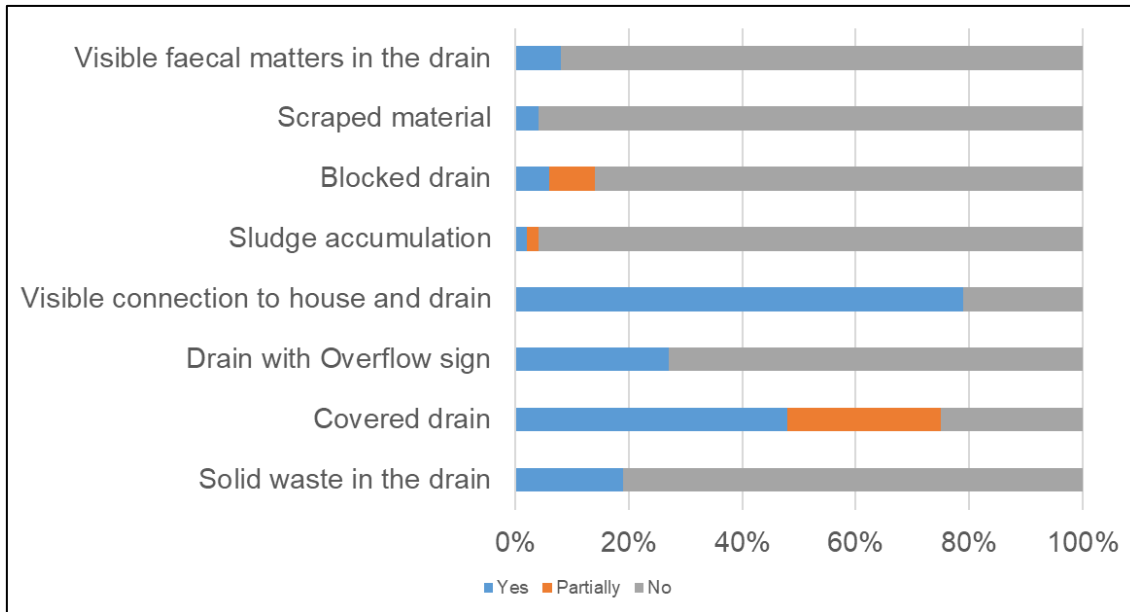


Figure 4.6: Summary of direct field observations. The total number of sampling point was (N=58), 10 of which were conducted outside the prototype model area in wider Western catchment.

The bar plot illustrates eight evaluated sanitation attributes in Rajshahi city: visible faecal matter, scrapped material presence by the side of the drain, blocked drains, sludge accumulation in the drain, visible building-to-drain connection, signs of overflow, covered drains, and solid waste in drains. The results, converted to percentages, indicate each attribute's presence (Yes), partial presence (Partial), or absence (No). Notably, scrapped material presence, blocked drains, and sludge accumulation in the drain were considered indicators of faecal presence, alongside visible faecal matter, cumulatively accounting for 30% of the sampling points. The study also reveals that approximately 80% of buildings have visible connection to a drain. The majority of drains (75%) are either fully or partially covered. Other observations include the presence of solid waste in drains at around 20% of locations and signs of overflow in approximately 25% of the locations.

Identifying faecal matter in the drain is challenging because the moisture content of fresh faecal matter can range from 60 to 85% (Woolley et al., 2014). On top, the user uses toilet flush which causes faecal matter to be mixed and diluted with water. Furthermore, a person uses another ~100 l of water on a daily basis which also ends up in the drains where escaped faecal matter from the septic tank gets diluted again. Given that dilution is an ongoing process and repeats downstream of each building, the ratio of grey water to escaped faecal matter is extremely high making it difficult to distinguish faeces from water. At only one out of 48 observation points were faeces visually-identified in the drain. However, a

number of indicators are used to identify the presence of faecal matter in the drain. The three indicators (scraped materials, blocked drain, sludge accumulation in the base of the drain), as shown in Figure 4.6, point to signs of faecal matter transport from septic tanks. This 'sludge'—a semi-solid mixture of various waste materials, including organic waste, sediment, debris, and escaped faecal matter—forms a dense, viscous substance. The presence of faecal matter accelerates this accumulation due to its organic nature facilitating sediment aggregation (flocculation), making sludge an important indicator for clogging the open drains (Deng et al., 2022; Niwagaba et al., 2014). The indicators used may not be solely associated with faecal matter as other solid waste and road wash materials also gets trapped in the sludge. In approximately 30% of the observation points, these signs indicated the presence of faecal matter in the drain.

Drain scraping is a critical activity within the city's sanitation management system. The procedure is essential for preventing the overflow and to maintain a functioning drainage system for environmental health and urban well-being. The city corporation has a work force to manage and maintain the drain scraping regularly. Scraped sludge typically remains on the roadside for hours or even days to allow the liquid part to run off back to the drain, making it easier for city cleaners to transport the semi-dried material. During the fieldwork, there were relatively few drains with scraped-out sludge. Field observations highlighted the practicalities of this approach. For instance, during a specific operation at observation point 9 within the prototype area, sludge was left on the roadside overnight. By the subsequent day, it had been removed. This quick removal was the part of service improvement which helps to reduce potential health risks to the public.

Informal discussions with a cleaning team in ward 20, located on the eastern border of the western catchment, provided valuable insight into their operations. The team of 17 includes 10 members scraping drains and seven transporting sludge in rickshaws, which are designed as leak-proof but sometimes leak, to informal dumping sites on the outskirts of the city. They affirmed that recent

instructions from the city authority discouraged leaving sludge on the roads to minimize exposure hazards. On a daily basis, they manage to clean about 8 to 10 m (25 to 30 feet) of drain length and transport 3 to 4 van-loads, each carrying 100kg, of sludge. The vans, locally made rickshaws equipped with containers for carrying wet sludge, are intended to be leak-proof, though they often fail to meet this standard.

A significant expansion of flooding throughout the city during the rainy season, particularly at junctions where numerous secondary drains converge before joining the primary drain was noted. The sludge accumulation most likely influences the flooding as it reduces the flow capacity. Within our model area, the northeast corner was especially susceptible to flooding. Moreover, flooding also occurred in the northwest corner of the model area, mainly due to water inflow from a nearby sub-catchment. This floodwater dispersed drain sludge widely, and as the floodwater receded, we discovered a layer of residue on the roads and dry roadside areas. These observations offer crucial insights into the dynamics of urban flooding and its role in spreading faecal-contaminated sludge throughout urban areas.

Commercial areas, particularly on the model area's eastern side, are concentrated with health care facilities, and the location is close to the largest government medical college hospital. These areas, which extend to the north-eastern boundary, draw a significant number of people, thus augmenting the daytime population. Notably, many commercial buildings in these areas have a residential function as well, with residences typically situated on the upper floors. All the commercial floors contain toilet facilities. Although faecal production in commercial and residential buildings might be similar, the influx of daytime population in these dual-purpose buildings could potentially increase their contributions. This is a critical factor to consider in designing sanitation management systems.

The comparison between the model output and field observations showed an 80% consistency with the modelled flow direction (Figure 4.7). However, inconsistencies were noted because these drains were installed with gradients

opposing the natural slope (in order to maintain the incidence of overflow situations), leading to the observed discrepancies. The survey data has been analysed with respect to the current prototype area and compared the diagram (Figure 4.7).

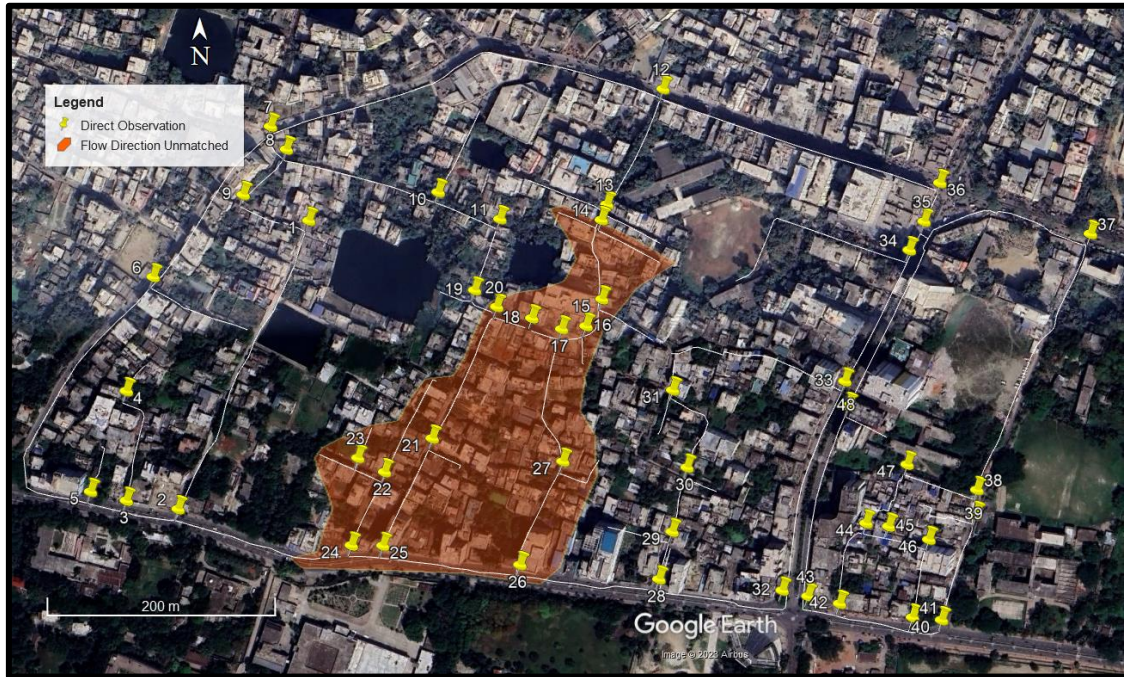


Figure 4.7: The 48 drain connection points have been directly observed in this area to compare the prototype model with the reality. The flow direction comparison is seen here. The unmatched flow direction was shown in the coloured area; in this area, storm drains are utilised to redirect water, and they have been created with gradients that are the opposite of the natural slope.

4.7.2 Informal Interviews

Meetings with local government specialists revealed that there was no formal system in place for collecting sanitation service delivery statistics, such as how many buildings empty their septic tanks yearly/monthly. Nobody knew the exact number of buildings connected to the drainage system. Most of the buildings use septic tanks, some of which are connected to soak pits while others are connected to drains. Formally, buildings were not supposed to use septic tanks directly connected to the drain; instead, they were expected to use soak pits (HBRI, 2015). However, it was brought up during the conversation that the practice of house drain connection is widespread because there is no formal

monitoring and enforcement. These connections often create almost direct linkages from the septic tanks to the drains, suggesting an absence of intermediary soak pits, particularly if the building is very old. This was affirmed through discussions with drainage workers. It was further noted, from these conversations, that some soak pits were connected to the drains to mitigate overflow. This is due to a rise in water table during the rainy season, causing soak pits to be ineffective. Moreover, soak pit designs varied across individual buildings. While some maintained grain-size stratifications in their filter design, others discreetly included an overflow connection with the drain.

In each ward of the city, the city corporation employs a team to manage the drainage systems through sludge scraping and cleaning the blockage. Contrary to the prototype model's assumption that all generated faecal matter reaches the outlet, the team cleans drains as on-demand services when blockages occur. However, this service is not immediate or entirely efficient due to potential upstream sludge accumulation that can cause recurring blockages. This insight came from the informal conversation with local residents.

Because there is no recorded data available, estimating the volume of sludge removed from the drains presents a significant challenge. This uncertainty challenges the assumption that all faecal sludge is transported to the catchment outlet. Consequently, any calculation or model developed under this assumption does not fully capture the actual dynamics of sludge removal. Therefore, it is essential to approach such estimates with caution, acknowledging the potential discrepancies between assumed and actual sludge movement within the drainage system. The city has mainly two types of emptying system. The city corporation has an emptying truck they emptied the septic tank on demand and take it to the informal dumping site located in the outskirts of the city in the northwest corner. The city authority does not maintain records on the number of trucks used, but they do keep some form of records regarding truck assignments, primarily for the purpose of fuel billing. Another type is manual emptying system, this is also on demand service and individually managed. When a homeowner calls the cleaner, who is typically self-employed, they arrive and empty the septic

tank. They frequently dump the sludge into the nearest primary drain since it is more convenient and less expensive to do so because the dumping site is outside the city.

4.7.3 Focus group discussion

The focus group discussion revealed that individuals are generally unaware of sanitation management, particularly regarding how faecal management is happens or why it is important. However, they indicated that in their area of the city, septic tanks and drains are connected. When asked about the use of emptying trucks, none of the participants reported ever seeing one, implying that they do not utilise such vehicles to empty their septic tanks.

The participants reported frequent instances of drainage overflow, particularly during the rainy season. They also confirmed that heavy rainfall events and flooding are closely related and that faecal matter is sometimes visible during these events. Moreover, they noted that drain sludge often ends up on the roads after floods, leaving a layer of dark grey muddy residue.

Upon discussing the issue of scraping, all participants confirmed witnessing this practice in their areas. The sludge is often left overnight to allow the liquid to drain, after which the solid sludge is removed by the city's cleaning team. When asked about the duration of sludge storage and whether the time span for leaving the slurry sludge behind was reducing, the response was affirmative, which corroborated the information gathered from other informal conversations within the prototype model area.

Although the group recognised the clear link between environmental pollution and sanitation, it was evident that participants had limited knowledge about the sanitation management system in their respective areas. Despite this, the insights gathered from the focus group discussion yielded invaluable confirmations of the direct observations, contributing significantly towards achieving the research aim.

Table 4.2: Summary of the results of the direct observations, informal interviews, and focus group discussions and indicating the extent of confirmation of the assumptions.

Assumptions	Observation	Data Source	Level of Confirmation	Implications for the prototype methodology
All septic tanks are connected to the drains rather than a soak pit	Around 80% of buildings are connected to drains, according to direct observation and survey data. Informal interviews and focus group discussions confirmed this widespread practice, although it is not the official expectation. Some soak pits are also connected to drains to prevent overflow, particularly during the rainy season.	Direct Observations, Informal Interviews, Focus Group Discussions	Medium / High	The prototype methodology will give precedence to drain connectivity in its spatial representation. There is a need to determine representative criteria for buildings linked to soak pits rather than drains, to exclude the contribution from the drain.
Septic tanks connected to	An informal talk with a member of the sludge	Direct Observations, Informal	Medium	The methodology should consider local septic tank emptying practices,

drains are not emptied	<p>emptying management team and a focus group discussion indicated that septic tank emptying service via the emptying track is not widely used.</p> <p>Also, the use of manual emptying systems is prevalent, where sludge is often dumped into the nearest primary drain.</p>	Interviews, Focus Group Discussions		particularly manual emptying. Also, identifying map able criteria for buildings undergoing emptying is vital to exclude their drain contributions.
All of the sludge entering the drains from buildings is transported to the catchment outlet	<p>Sludge entering to the drain was evidenced by the presence of sludge in drains, blockages, scraped sludge by the side of the drain and post-flood mud layers on roads. But all the sludge transported to the outlet was</p>	Direct Observations, Informal Interviews, Focus Group Discussions	Medium	The method should account for faecal accumulation in drains, excluding the amount of sludge scraped off.

	not true because the scraped sludge transported to the informal dumping side, outskirts of the city.			
Faecal matter is produced at all buildings irrespective of their types	Commercial areas, particularly those with dual-purpose buildings (residential and commercial), likely produce more faecal matter than that assumed in the model due to the influx of the daytime population. All commercial floors observed contained toilet facilities.	Direct Observations	Medium	The methodology should distinguish between building types and potentially assess population influx in commercial zones to measure faecal matter production reliably.
Every building has a toilet and septic tank	Majority of the buildings use septic tanks, although the city authorities do not have exact data on this. Informal	Informal Interviews	Medium / Low	The methodology should consider adjusting for variability in containment designs. Specifically, differentiation might be needed for pit latrines or buildings lacking toilets, such as warehouses.

	<p>interviews revealed the widespread presence of septic tanks, including the older buildings built before the 1980s. However, the septic tank's design and connection to the drain may differ.</p>			
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4.8 Discussion

4.8.1 The model vs reality: fieldwork findings

The fieldwork findings not only support the merits of open-source data but also showcase how the prototype methodology can be paired with traditional methods to bring about a spatial representation with reduced uncertainty. However, the assumption that all buildings connect to the drainage system may not be the reality. This study, through the fieldwork, confirmed that open-source data, while useful, could not provide all necessary details such as which buildings have soak pits, use emptying services, or information about drain scraping (Table 4.2).

The triangulation of methods — field observations, informal interviews, and focus group discussions — strengthens the validity and reliability of the model's findings (Patton, 1999). For instance, while open-source data empowers the modelling of spatial pattern of faecal matter generation and its movement, field observations serve as an indispensable ground truth, thus improving the model's trustworthiness. Blending qualitative and quantitative approaches enriches our

research, offering a comprehensive perspective (Table 4.2). This observation was validated by unstructured interviews and focus group discussions, highlighting the absence of a clear pattern of the buildings with septic tanks or soak pits connected to drains. However, no such trend was evident in the case of soak pits or septic tanks linked to drains. This lack of identifiable trends highlights the need for fieldwork and building-level surveys. However, the field study has emphasised the potential benefits of combining open-source data with monitoring and operation data.

4.8.2 Challenges and Areas of Methodology Improvement in Spatial Representation

Sanitation management often takes a back seat in city governance, generally addressed as part of other management activities (e.g., storm drainage maintenance). In cities like Rajshahi, this is because the drains were never designed to be a part of a city-wide sanitation network. Consequently, no proactive framework exists for managing, maintaining, or monitoring sanitation processes. The scarcity of sanitation data, which was observed during the informal interviews, stresses this fact. The sub-catchment prototype method can be employed using only open-source data, providing preliminary spatial insights. However, its effectiveness and accuracy would be significantly enhanced if supplemented with data from municipal sanitation professionals. If feasible, conducting targeted fieldwork will further enrich the outcomes (Figure 4.6).

Yet, the validation process for representing buildings in cities is riddled with challenges and uncertainties. For instance, each house could have multiple connections to the drainage system (including grey and black water pipes), some of which may not be visible, but nonetheless exist (Bari, 2017). Informal discussion revealed that pipe connections are often installed beneath the drain's lowest water level, making them invisible.

Moreover, city authorities typically provide on-demand sanitation services. They respond when residents request assistance but do not often maintain data about these service calls. Their records tend to focus on service deliveries for specific activities, such as the addresses requiring truck dispatches. Although not

originally intended for sanitation improvement, this data could potentially be leveraged for sanitation management purposes. The service book contains the street name (not which building) where emptying service happened, this information can be incorporated in future in the spatial analysis.

Gathering field data, recording and maintaining databases, as well as conducting data analysis and reporting, are cost-intensive processes, often leading to their limited implementation. However, the integration of open-source data with these activities could significantly enhance the accuracy of the model. This combination would provide a more precise depiction of real-world situations, thereby improving the model's precision and effectiveness.

Despite these challenges, spatial representation at the building level could lead to significant benefits if city authorities consider applying the model for individual building service delivery. While the spatial scale is smaller, this still has the ability to obtain data that can offer detailed insights into the sanitation situation. Fieldwork and building-level surveys can help us gather information about which buildings have soak pits, use emptying services, or have information about drain scraping.

The method addresses the intersection of sanitation management and open-source data, filling gaps in our current understanding and contributing to more effective and reliable utilisation of these emerging resources for sanitation management. This kind of model can enable city authorities to identify which building or street needs attention, potentially addressing a problem that could affect the entire downstream catchment.

While storm drainage systems are not typically intended to serve as faecal management systems, practical realities often necessitate such repurposing in many cities lacking centralised or decentralised faecal management systems. Thus, the modelling using open-source data proposed by Sultana et al. (2023) could be enriched with field observations and further informed by monitoring and operational data. Currently, the main challenges include the exposure to faecal contamination due to flooding and desludging of drains, and the nuisance caused by odour. To mitigate these risks, an interim solution could be implemented for

sanitation management. This would involve using the model to understand the spatial dynamics of faecal generation and movement, allowing city authorities to prioritise their efforts to desludging the drain and the maintenance more effectively. Monitoring and operational data, such as locations and frequencies of emptying or scraping activities, could serve as valuable inputs. For instance, in a city, faecal sludge that escapes the containment can increase the accumulation rate in the storm drain and may not reach the outlet as it could settle in the drain first (Deng et al., 2022; Niwagaba et al., 2014). Therefore, managing the sludge through regular scraping, and identifying the underlying causes with the help of operational data, can contribute to improved sludge management. This not only aids in reducing the risk of flooding but also ensures the free flow within the drains, all while proper containment and treatment facilities are being established.

4.8.3 Contextual Implications of Spatial Representation

Sanitation management operates within a complex, multi-scale environment (Hyun et al., 2019; Scott et al., 2015). The prototype model, which represents a small hydraulic sub-catchment – a unit within a larger catchment where both rainwater and wastewater meet into drains that eventually lead to the catchment's outlet. These sub-catchments, adhering to a hydraulic hierarchy, combine to form a larger catchment (Li et al., 2020).

City authorities often partition the city into multiple wards for administrative purposes and service delivery. Despite being predominantly used for administrative activities like storm drainage and sanitation, the natural hydrology of many cities often aligns these wards with hydrological sub-catchments. As confirmed through informal dialogues with sanitation professionals and focus group discussions, the city is divided into 30 wards, each with its own reactive management system. The alignment of administrative boundaries with hydrology provides an opportunity to use the spatial representation approach for planning purposes.

One challenge identified with the prototype model is the lack of granular data at the building level, especially regarding factors influencing faecal matter movement. These are the emptying of septic tanks, the use of soak pits, and

sludge removal from drains, variations in faecal matter production by building types, and the presence or absence of toilets. While this precise data may not be readily available, city authorities might be able to obtain reliable statistics at the ward level, shedding light on practices like, emptying services, and drain scraping. For example, the city council could track the number of sludge emptying trucks servicing a particular ward over specific periods, such as monthly or annually. Representing this data at the ward level allows a more sophisticated understanding of sanitation management, essentially adding another layer to the current model. This enhanced perspective would serve as a crucial resource for informed planning, strategic development, and the efficient allocation of resources. Also, by incorporating actual population data instead of estimated figures from LandScan, the up scaled model could enhance accuracy and confidence in sanitation management at the ward level.

4.9 Conclusions

The fieldwork conducted as part of the study aimed to assess the validity of assumptions and where possible the model outputs in the test catchment. Conducting fieldwork led to a broader understanding of the sanitation system in Rajshahi, and helped in evaluating the reliability of model assumptions informed by open-source data.

A qualitative comparison of the model output with field observations revealed an 80% consistency in the modelled flow direction and drainage connection with the buildings. Also the fieldwork provided valuable confirmatory insights into the influencing assumptions of spatial variability in faecal matter movement e.g. the existence of septic tank emptying, using soak pits, and drainage desludging but there was no recorded data for this purposes.

However, it is not possible to directly capture the actual quantity of practices such as septic tank emptying, use of soak pits, and drain scraping from open-source data. These factors, along with challenges like blocked drains and overflowed drains, especially during the rainy season, highlight the need for fieldwork.

In the context of sanitation management in unsewered cities, the literature reveals a notable gap in methodologies for spatial characterisation of urban sanitation. The exception to this is the work by Peal et al. (2014), which introduced the Shit Flow Diagram (SFD) model. This model presents a framework capable of representing aggregated scenarios for entire cities, offering a unique approach in this field. However, it is important to acknowledge that this model, while pioneering, may not fully address the granularity required for spatial characterisation in specific urban contexts.

The study emphasises the potential of the Sultana et al. (2023) model in addressing the spatial variability inherent in the production and movement of faecal matter. This model, offers its reliability, provides foundational spatial characteristics of faecal production and movement, marking a significant step forward in understanding and managing urban sanitation dynamics in absence the recorded data.

The field observations and informal discussions have identified two key issues: firstly, the absence of detailed building-level data hinders the refinement of the model at the sub catchment scale using in situ data. Secondly, the city corporation manages sanitation services at the ward level - the smallest administrative unit - but there is no recorded sanitation data at the ward level.

These insights imply that for the model to be effectively applied in the city's current context, an adaptation to a level that aligns with the city corporation's operational framework would be more beneficial. Such an adaptation would result in a model that is more detailed than the Shit Flow Diagram (Peal et al., 2014) but less detailed than the sub-catchment model proposed by Sultana et al. (2023). This would create a new model, suitable for city-scale application. While service delivery records at the ward level are not consistently maintained, adapting the model to this scale offers the opportunity to integrate future data. Furthermore, it makes the model a more practical tool for managing the city's sanitation needs.

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References

- Amin, N., Liu, P., Foster, T., Rahman, M., Miah, M. R., Ahmed, G. B., Kabir, M., Raj, S., Moe, C. L., & Willetts, J. (2020). Pathogen flows from on-site sanitation systems in low-income urban neighborhoods, Dhaka: A quantitative environmental assessment. *International Journal of Hygiene and Environmental Health*, 230, 113619. [https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113619](https://doi.org/10.1016/j.ijheh.2020.113619)
- Bari, M. N. (2017). Study on Existing Faecal Sludge Management Situation in Rajshahi Rajshahi City. *Proceedings of the WasteSafe 2017 – 5th International Conference on Solid Waste Management in South Asian Countries 25-27 February 2017, Khulna, Bangladesh STUDY, March*.
- Clemett, A., Amin, M., & Ara, S. (2006). *Background Information for Rajshahi City, Bangladesh*.
- Deng, Z., Huang, D., He, Q., & Chassagne, C. (2022). Review of the action of organic matter on mineral sediment flocculation. *Frontiers in Earth Science*,

10. <https://doi.org/10.3389/feart.2022.965919>

Ekklesia, E., Shanahan, P., Chua, L. H. C., & Eikaas, H. S. (2015). Temporal variation of faecal indicator bacteria in tropical urban storm drains. *Water Research*, 68, 171–181. <https://doi.org/https://doi.org/10.1016/j.watres.2014.09.049>

Foster, T., Falletta, J., Amin, N., Rahman, M., Liu, P., Raj, S., Mills, F., Petterson, S., Norman, G., Moe, C., & Willetts, J. (2021). Modelling faecal pathogen flows and health risks in urban Bangladesh: Implications for sanitation decision making. *International Journal of Hygiene and Environmental Health*, 233, 113669. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113669>

HBRI. (2015). *Bangladesh National Building Code*.

Hyun, C., Burt, Z., Crider, Y., Nelson, K. L., Prasad, C. S. S., Rayasam, S. D. G., Tarpeh, W., & Ray, I. (2019). Sanitation for Low-Income Regions: A Cross-Disciplinary Review. *Annual Review of Environment and Resources*, 44(1), 287–318. <https://doi.org/10.1146/annurev-environ-101718-033327>

Islam, M. S., Islam, S. M., & Islam, A. M. (2021). Assessment of efficacy of drainage system in Rajshahi City Corporation, Bangladesh. *Advances in Environmental Research*, 10(2), 105–116. <https://doi.org/10.12989/aer.2021.10.2.105>

Leidig, M., Teeuw, R. M., & Gibson, A. D. (2016). Data poverty: A global evaluation for 2009 to 2013 - implications for sustainable development and disaster risk reduction. *International Journal of Applied Earth Observation and Geoinformation*, 50, 1–9. <https://doi.org/https://doi.org/10.1016/j.jag.2016.03.001>

Li, C., Fan, Z., Wu, Z., Dai, Z., Liu, L., & Zhang, C. (2020). Methodology of sub-catchment division considering land uses and flow directions. *ISPRS International Journal of Geo-Information*, 9(11). <https://doi.org/10.3390/ijgi9110634>

Mills, F., Willetts, J., Petterson, S., Mitchell, C., & Norman, G. (2018). Faecal

- pathogen flows and their public health risks in urban environments: A proposed approach to inform sanitation planning. *International Journal of Environmental Research and Public Health*, 15(2). <https://doi.org/10.3390/ijerph15020181>
- Niwagaba, C. B., Mbéguéré, M., & Strande, L. (2014). Faecal Sludge Quantification, Characterisation and Treatment Objectives. In L. Strande, M. Ronteltap, & D. Brdjanovic (Eds.), *Faecal Sludge Management Systems Approach for Implementation and Operation* (pp. 19–44). IWA Publishing.
- Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Services Research*, 34(5 Pt 2), 1189.
- Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., Schoebitz, L., Scott, R., Sleigh, A., Strande, L., & Veses, O. (2020). Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned From a Global Implementation of Excreta-Flow Diagrams. *Frontiers in Environmental Science*, 8, 1. <https://doi.org/10.3389/fenvs.2020.00001>
- Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2014). Fecal sludge management (FSM): analytical tools for assessing FSM in cities. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 371–383. <https://doi.org/10.2166/washdev.2014.139>
- Scott, P., Cotton, A., & Sohail, M. (2015). Using tenure to build a “sanitation cityscape”: narrowing decisions for targeted sanitation interventions. *Environment and Urbanization*, 27(2), 389–406. <https://doi.org/10.1177/0956247815569415>
- Sercu, B., Van De Werfhorst, L. C., Murray, J. L. S., & Holden, P. A. (2011). Sewage Exfiltration As a Source of Storm Drain Contamination during Dry Weather in Urban Watersheds. *Environmental Science & Technology*, 45(17), 7151–7157. <https://doi.org/10.1021/es200981k>
- Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B. J., & Niwagaba, C. B. (2018). Methods to reliably estimate faecal sludge

quantities and qualities for the design of treatment technologies and management solutions. *Journal of Environmental Management*, 223(June), 898–907. <https://doi.org/10.1016/j.jenvman.2018.06.100>

Sultana, M. S., Waine, T., Bari, N., & Tyrrel, S. (2023). Towards a new spatial representation of faecal sources and pathways in unsewered urban catchments using open-source data. *Journal of Water, Sanitation and Hygiene for Development*, 13(4), 289–300. <https://doi.org/10.2166/washdev.2023.227>

Tabassum, S. (2020). Drainage system, its water quality and health effect: A case study of Rajshahi city, Bangladesh. *Scientific Journal of Environmental Sciences*, 9(1), 323–336. <https://doi.org/10.14196/sjes.v9i1.2612>

Woolley, S. M., Buckley, C. A., Pocock, J., & Foutch, G. L. (2014). Rheological modelling of fresh human faeces. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 484–489. <https://doi.org/10.2166/washdev.2014.088>

5 CITY-SCALE SPATIAL MAPPING OF FAECAL PRODUCTION AND MOVEMENT IN UNSEWERED URBAN AREAS: SANIFFLOW – AN INTEGRATED PLANNING AND MANAGEMENT TOOL⁵

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5.1 Highlights

- SanIFFlow: is a new method for spatial analysis in unsewered urban sanitation
- SanIFFlow highlights the aspects of faecal matter movement in relation to spatial population distribution
- Uses accessible data to create comprehensive maps of urban sanitation issues
- Offers a new, data-driven approach to tackle urban sanitation challenges.

5.2 Abstract

Adequate sanitation is indispensable for public health in cities worldwide. However, planning and managing sanitation system in secondary cities in

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economically developing countries remains a persistent challenge due to a lack of spatial understanding and representation. To address these challenges, this study introduces SanIFFlow (Sanitation Infrastructure and Faecal Flow), a spatial analytical approach that can be adjusted to both sub-catchment and catchment levels. Here SanIFFlow transitions from a detailed building level model to an up scaled ward-level model, providing comprehensive coverage of both infrastructural attributes and flow aspects in urban sanitation management. This shift from building level to ward level of the city, ward, the smallest administrative units, as primary units for faecal production sources, coupled with the identification of major drains as key pathways, aligns spatial modelling with practical governance capacities and scales. Employing open-source data on buildings, population, and ground elevation, this study offers a spatial representation of the sources and pathways of faecal matter movement across the catchment. This city-scale model demonstrates potential utility for strategic sanitation assessments, enabling proactive management and decision-making. The approach will facilitate the identification of high-risk areas in need of priority intervention and support the planning of targeted actions. Such actions might identify wards for containment upgrades or coordinating drain rehabilitation efforts across multiple wards. The SanIFFlow approach offers significant guidance for centralised planning and management in urban sanitation. This can be a valuable tool for municipalities who are seeking to enhance their sanitation management capabilities.

Keywords: SanIFFlow; Urban sanitation; Faecal matter movement; Spatial analysis; Municipal planning.

5.3 Introduction

Managing urban sanitation effectively remains a complex and growing challenge, particularly unsewered urban areas (Peal et al., 2020). There is a pressing need for new approaches in the spatial management of sanitation, yet a significant knowledge gap exists regarding the ideal spatial scale for faecal sludge management in cities.

Citywide Inclusive Sanitation (CWIS) frameworks aspire to transform urban sanitation systems, advocating for equitable, safe, and sustainable solutions, particularly for the urban poor (Schrecongost et al., 2020). However, operationalizing these frameworks involves challenges such as increased awareness, development of precise data metrics, financial system reform, planning processes, and policy incorporation (Gambrill et al., 2020). Despite recent advancements in urban sanitation scholarship, a comprehensive integration of these studies into a unified CWIS narrative, particularly regarding spatial representation and financial considerations, is implied but not explicitly addressed in the overarching review and editorial summary by (Lüthi et al., 2020).

The Shit Flow Diagram (SFD), a widely used tool, while revolutionary in providing a visual representation of complex sanitation data, focuses primarily on the physical flow of faecal waste, often overlooking the financial and contextual aspects (Peal et al., 2014, 2020). This limit emphasises the need for a more comprehensive integrated approach, particularly given the inconsistent data and sustainability from a financial standpoint. Research that incorporates householders' investment logic into an FSM planning framework, exemplified in the 'Sanitation Cityscape' model (Scott et al., 2015; Scott & Cotton, 2020), highlight the importance of considering diverse aspects of sanitation management. While this framework provides a comprehensive view of Household Centred Environmental Sanitation (HCES) model for fate of faecal waste in a city, its direct application to the practicalities of spatial representation remains limited. Also, The CLUES (Community-Led Urban Environmental Sanitation) framework, which promotes a community-led, holistic, and inclusive approach. However, this was found to be expensive, time consuming, and politically challenging in Luchenza, Malawi. Stakeholder participation was limited and relied on incentives (Mtika & Tilley, 2020). Similarly, (Willets et al., 2020) present a case study on co-management approaches for community-scale sanitation systems in Indonesia, focusing on the role of local government and institutional arrangements. Yet, this study does not delve into the specifics of identifying neighbourhood-level issues. Additionally, the Urban Sanitation Status

Index (USSI) introduced by (Hawkins & Muxímpua, 2015) offers a business model for assessing neighbourhood-level sanitation status, but it also highlights the need for more detailed data on costs and services.

These diverse strands of research collectively reveal a landscape filled with innovative ideas and methodologies but also highlight a crucial gap: the absence of a standardised method for spatial characterisation and a clear understanding of how spatial scales, coupled with financial and operational considerations, affect practical sanitation management. In addressing this gap, this paper explores the reliable spatial scale for representing urban sanitation in economically developing countries. A recent study in Rajshahi, Bangladesh employed building-level data for sub-catchment modelling, enabling identification of faecal production sources and movement pathways (Chapter 2, Sultana et al., 2023). Using this approach, preventative measures can be tailored by simulating specific buildings, their faecal matter output, and drainage links. Such granularity has the potential to highlight locations prone to blockages and guide actions like local drain rehabilitation. This detailed perspective offers vital insights, fostering neighbourhood sanitation planning that entire city-wide models (Peal et al., 2014) might miss. Also, an uncertainty and sensitivity analysis of the model simulated at the neighbourhood scale revealed how minor localised factors can have unintended, large-scale impacts when mapped across an area (Chapter 3).

In the Rajshahi study field observations indicated that the city's current administrative capabilities were not prepared to adopt this sub-catchment level model (Chapter 4). This is because of two critical issues identified during the field observations and informal discussions: firstly, the absence of detailed building-level data hinders the refinement of the model at the sub-catchment scale using in-situ data. Secondly, the city corporation's management of sanitation services at the ward level — the smallest administrative unit — necessitates adjusting the existing model to this level to be an effective tool. In response, we developed a city scale (coarser-scaled, ward-level) modelling approach, aligning better with the overarching needs of city-wide sanitation planning. Through this exploration, we aim to contribute to the broader goal of effective city-scale sanitation

management, while being aware of collecting data and the underlying need for resource allocation.

5.4 Data and Method

5.4.1 Study Area

This work builds on the foundational model of faecal movement sources and pathways developed in Chapter 2 by Sultana et al. (2023) in Rajshahi, Bangladesh. It extends the focus from sub-catchments, $\sim 0.3 \text{ km}^2$, (using building-level data) to a city-scale, $\sim 25 \text{ km}^2$, (coarser ward-level) analysis within the western catchment, encompassing 19 of the city's 30 wards.

5.4.2 Data

For effective city-wide sanitation planning, this study introduces a broader scale modelling approach that prioritises wards (the smallest administrative unit of the city). While the previously utilised sub-catchment level modelling provided invaluable insights at a more granular scale, there was a recognition that a broader scope could offer a more practical solution. This model differs from the sub-catchment model, which identifies faecal production sources and pathways based on the densities of specific buildings and populations. In contrast, this approach treats city wards as the primary units for faecal production, rather than individual buildings. Additionally, it focuses on major drains as the key pathways, rather than including all drains in the area. The aim is to offer a city-scale framework for effective sanitation management.

This analysis requires three key pieces of data: ward boundary data (Rajshahi city has 30 wards), ward population data, and drainage data (Bari & Kabir, 2023). If these are not readily available, the model can use open-source data, which has been the case here. For this study, remote sensing data was used due to its accessibility and versatility. The drainage data used is identical to the one used earlier, but the focus was shifted to major drains.

5.4.3 Estimating Faecal Production

This study utilises the approach of the previous sub-catchment analysis by assigning gridded population data to individual buildings in accordance with their respective volumes and then aggregated the amounts in each ward (Figure 5.1). Building volume is calculated using data on building height and area respectively. Once the population in each building is determined, faecal production is estimated assuming a production rate of 250 g/d/person (Niwagaba et al., 2014; Rose et al., 2015). The faecal production for the entire ward is then computed by aggregating the estimates from all buildings within that ward.

If ward-level population data is available, the model could bypass the need for the aforementioned steps, enabling a more direct calculation of faecal production within each ward.

5.4.4 Determining Faecal Movement Pathways

In the previous sub-catchment analysis, all three types of drains were included as pathways for faecal matter movement, the major drains called primary drain which are bigger drains in the area. These drains receive wastewater from secondary and tertiary drains, relatively smaller drains which mostly have direct connection with the buildings. Here in the city-scale model only primary drains in each ward have been considered as the pathways of faecal matter movement (Figure 5.1). This shift from focusing on local drains, which comprise interconnected tertiary and secondary drains expelling wastewater from buildings, to major drainage channels, represents a key element of the up scaled model. Unlike the narrower local drains, typically covered with concrete slabs and often less than 1 meter wide, the major drains (Figure 4.3) are larger and uncovered, engineered with concrete walls, and feature wider and deeper dimensions. Originally natural and formed by topographic depressions, many of these major drains have been modified and lined with concrete to enhance their capacity and durability. By aggregating buildings into wards and concentrating on these primary drainage channels, the up scaled model aims to capture the larger scale dynamics of faecal production and movement, providing a high-level yet spatial picture of urban sanitation.

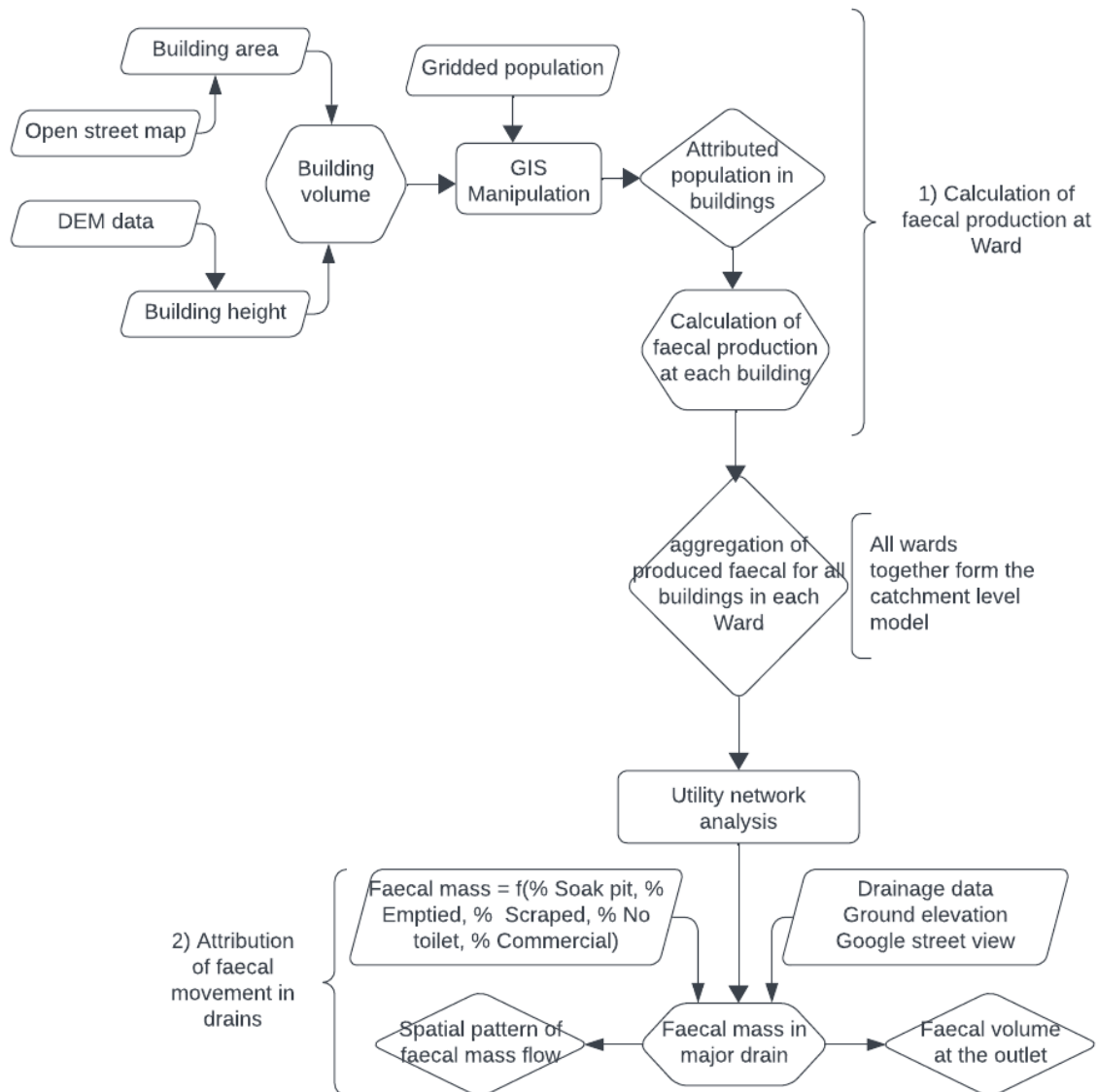


Figure 5.1: Flow diagram for an up scaled ward-level model based on open-source data. There are two important steps: estimation of faecal production in wards and attribution of faecal movement in drains. The symbols used are conventionally applied: the rectangle represents a process, the parallelogram represents data collection, the hexagon indicates preparation steps, and the diamond signifies decision points.

5.4.5 Ward to Drain Connectivity and Sankey Representation of Faecal Movement

Scaling up from the building-level analysis conducted in the previous sub-catchment work (Chapter 2), this study focuses on ward-level connectivity. To map out these connections, a geographical information system (GIS) proximity analysis is adopted, wherein the centroid of each ward (assumed location of faecal production) is linked to the nearest main drainage channel. This assumes that all faecal matter produced within a ward ultimately finds its way to the primary drain of that ward.

This approach allows for the creation of a drainage network map at the ward level, highlighting the connections between sources of faecal production and their primary drainage pathways. The flow direction of each major drain is identified using natural slope analysis, information about engineered drains, and where available, Google Street View data.

A Sankey (Schmidt, 2008) approach is then applied to visually represent the estimated flow of faecal matter through the city's primary drainage system. In these Sankey diagrams, the width of the lines corresponds to the estimated mass flow of faecal matter, providing an intuitive visualization of where the largest amounts of faecal matter are flowing.

5.5 Results

5.5.1 Population distribution in wards

In the model (Figure 5.2), the population was first distributed among buildings and then aggregated into wards, with each ward containing approximately 1,300 to 5,000 buildings and hosting 15,000 to 20,000 people. The average number of people per building, that are typically 3 to 4 stories, is approximately 10. The map presents a visual representation of population distribution within Rajshahi city's Western Catchment area. Each ward is numerically labelled, and dots indicate central points for reference. The legend details the population range for each colour, starting from a lighter shade for wards with a population as low as 6,000, to the darkest shade representing wards with a population as high as 43,300.

Such detailed demographic data is vital, as it informs us that wards with darker shades, such as Ward 20, are likely to have higher faecal matter production due to their greater population density.

5.5.2 Faecal production at wards and their pattern

Figure 5.2 illustrates the spatial distribution of faecal mass flow within the western catchment of Rajshahi city, which is closely linked to population density. The centre points denoted inside each ward serve as a spatial reference that connects the population data of the particular ward. The spatial analysis shows a clear northward direction of rising faecal load within the drainage system. This pattern is a result of the confluence of drainage from multiple wards into larger canals, thereby reflecting the accumulative nature of the waste flow. The most substantial flows are observed in Ward 16, extending to Ward 18, where the volume of faecal mass ranges between 1,190 and 2,940 ton/year. These wards have been identified as critical zones for waste accumulation, signalling the urgent need for effective sanitation management strategies, both within these areas and upstream.

5.5.3 Faecal movement and Sankey representation.

The Sankey diagram (Figure 5.2) offers a visual representation of faecal matter movement within the wards of the study area. The diagram delineates the faecal mass flow, with variations in width of line indicating the relative volume of faecal material being transported: thicker lines indicate higher volumes, signalling more substantial faecal accumulation, moving northward, culminating at the catchment outlet.

In the context of the wards, the line thickness correlates with the ward's population and, consequently, the expected faecal load.

The classification range for the spatial accumulation of faecal matter in the GIS map was established with careful consideration of both the typical population sizes in smaller areas and the natural breakpoints in the hydrological network. For example, faecal mass flow volume 600 ton/yr represents areas with the minimum population sizes found in the wards, coinciding with the streams in the

headwater parts of the catchment. This class reflects the initial stages of the drainage network where the faecal load is comparatively lower due to smaller population contributions.

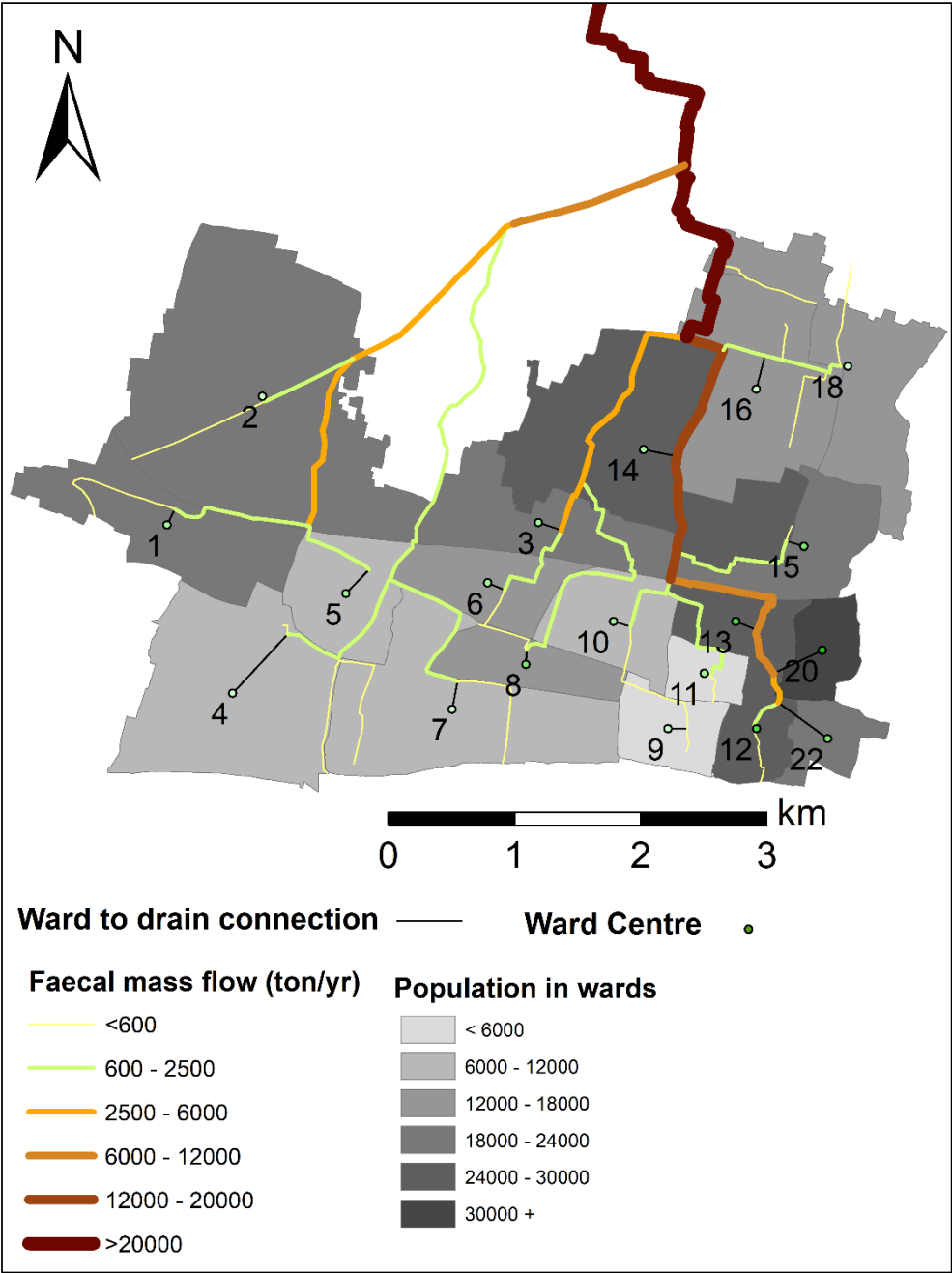


Figure 5.2: Faecal mass flow in the western catchment derived from faecal mass production at ward level. The map shows each ward connected to the nearest primary drain. The mass flow variations depend on the population in each ward.

Conversely, the uppermost class encapsulates the total faecal matter produced in the entire catchment area. This class is indicative of the point where all the drainage networks converge, representing the cumulative effect of the entire catchment's population. This approach in setting the classification ranges allows for a nuanced understanding of how both demographic factors and hydrological structures contribute to the spatial variability of faecal matter accumulation in the urban drainage system.

5.6 Discussion

5.6.1 Interpretation of the movement of faecal matter

The study reveals a direct correlation between population density and faecal matter dynamics in Rajshahi city's Western Catchment area. The northward increase in faecal accumulation, as depicted by the spatial analysis and the Sankey diagram (Figure 5.2), highlights the accumulative nature of faecal flow in downstream areas. Considering the city's hydrological profile, with a higher elevation in the south and a drainage network predominantly flowing northward (Dissanayake et al., 2007), the increased faecal production in higher-density wards like Ward 20 not only elevates local waste levels but also intensifies the faecal accumulation downstream areas in the north, particularly in Wards 16 to 18, where it reaches up to 3000 tons per year due to the converging drainage patterns.

This observation highlights the need for focused urban sanitation strategies in densely populated wards, as they are key contributors to both higher faecal production and the cumulative faecal flow in the drainage system, posing significant management challenges.

The primary drain's role in transporting significant quantities of faecal matter, and the associated risks of flooding and blockages, is a major concern for urban sanitation management. Identifying where faecal mass increases along the drain and implementing appropriate interventions are crucial to prevent environmental contamination.

Methodologically, integrating empirical ward-level data is key to enhancing the model's accuracy. While specific data on household septic tank emptying are challenging to obtain, aggregate data on septic tank services used within wards provide valuable insights for strategic planning. Collaborating with city stakeholders in implementing and refining the model is crucial for optimising urban health and environmental quality (Willetts et al., 2020).

The city-scale model demonstrates spatial variability in faecal matter production, with central, denser wards showing higher outputs compared to peripheral ones. The primary drainage channel, influenced by natural topography, merges waste flows from these wards, although the reliability of these findings is constrained by assumptions yet to be empirically validated. Ground-truthing at the ward level, involving surveys and monitoring, is essential to confirm these assumptions and refine the model. Nevertheless, the model is instrumental in identifying priority areas for sanitation infrastructure improvement.

5.6.2 Operational Frameworks and Spatial Considerations

The local authorities currently handle their administrative work at the ward level (Bari et al., 2018; Tabassum, 2020). Existing methods allow for the assessment of sanitation at both the aggregate assessment of the entire city (Peal et al., 2014) and the sub catchment level (Sultana et al., 2023). Understanding both these scales is crucial: the entire city offers a macroscopic view of sanitation service chain for a city, while the sub catchment level focused sources and pathways of faecal movement at individual buildings to street level within the city.

However, when it comes to making proactive, city-scale inclusive sanitation systems, neither scale fully aligns with practical needs. Entire city aggregated data often lacks the granularity necessary to understand the diverse contexts and heterogeneity within cities. In contrast, while building-level information provides that granularity, but most cities are not yet ready to serve in this scale due to constraints related to finance and data availability (Kelkar & Seetha Ram, 2019).

Sultana et al. (2023) identifies individual buildings as primary sources of faecal production, focusing on approximately 900 buildings within a sub-catchment scale. The further investigation revealed that these sub-catchments frequently

correspond to the city's ward structure, with some ward boundaries even reflecting the hydrological delineations of the sub-catchments. This interplay between administrative divisions and natural hydrological patterns presents an opportunity for integrated faecal management strategies.

Building on Sultana et al.'s research, this study expands the model to a broader spatial scale, specifically the western catchment of the city, encompassing 19 of the 30 wards. While the transition from a sub-catchment to a city-scale perspective offers a broader understanding, it also brings about challenges in terms of data aggregation and management precision. The sub-catchment scale, being more granular, allows for targeted interventions but may overlook broader systemic issues, whereas the city-scale approach provides a wide-ranging overview but could potentially miss localised nuances. Therefore, a balanced approach, perhaps a hybrid model combining both scales, might be the most effective way forward. This hybrid approach can leverage the detailed insights of the sub-catchment scale while also capitalising on the overarching perspective provided by the city-scale analysis. Here the transition from a sub-catchment to a city-scale perspective is not simply a change in scale, but aligns strategically with the city's existing administrative frameworks, thereby facilitating the implementation of effective faecal management strategies.

In managing the sanitation of these cities, understanding the infrastructure and the flow of faecal matter within the urban environment is critical. Both sub-catchment and ward-level models contribute essential insights into the faecal production and movement. We have termed this spatial analytical approach SanIFFlow (Sanitation Infrastructure and Faecal Flow), encapsulating its comprehensive coverage of both infrastructural attributes and flow aspects in unsewered urban sanitation management.

5.6.3 Data-Gathering Opportunities and Spatial Adaptability

Employing open-source data facilitates multi-scalar analysis, ranging from individual households to citywide ward level comparisons, revealing service delivery gaps at multiple levels. Working in different spatial scales enhanced the opportunities for understanding the detailed sanitation situation within the city and

the potential data gathering scope. This ward-level approach aligns with the operational scale currently employed by municipal authorities for sanitation services, such as septic tank emptying and drain sludge removal (Mtika & Tilley, 2020; Scott et al., 2015; Scott & Cotton, 2020). Despite the lack of systematic record-keeping by these authorities, the model's reliance on open-source data and its essential assumptions could be significantly enriched if municipal activities were documented and integrated (Table 5.1).

The spatial scale of a city's sanitation system is crucial, as wards function on a hydrological hierarchy, affecting downstream wards. There is currently no standardised visualisation or comparative tool to understand ward-to-ward variations in sanitation and drainage issues. Understanding the specific needs and capacities of city authorities is crucial for effective sanitation management strategies. A ward-level SanIFFlow approach, involving data collection and fine-scale models (Sultana et al., 2023), can be more effective, as identified wards with significant sanitation challenges can be addressed through deeper data collection. Such a framework would not only streamline city management efforts but also furnish a proactive strategy for sanitation oversight, pinpointing factors such as the regularity of septic tank emptying, the prevalence of soak pits, and the drains requiring frequent maintenance. This proactive approach could catalyse remedial actions at the source of sanitation issues, whilst simultaneously offering researchers a foundation for data validation and the delineation of future data collection endeavours.

Aligning the model with the city's ward boundaries offers city authorities a valuable framework. Wards normally have access to demographic data, which can be converted into estimates of faecal volume; additionally, sanitation service delivery data can be easily recorded (Table 5.1), facilitating the development of models that reveal broader patterns and trends in faecal matter flow throughout the city.

Table 5.1: Detailed data collection needs for ward-level sanitation modelling:
This table provides a systematic breakdown of essential sanitation attributes required for enhancing ward-level sanitation models. It highlights the necessary data inputs and their direct implications for refining and scaling up sanitation services effectively within city wards.

Sanitation Attributes	Data Need	Implications
Septic Tank Emptying Amount (kg/yr)	<ul style="list-style-type: none"> - Maintain regular records of the number of septic tanks emptied and the amount of sludge, e.g., how many trucks? - Calculate the total annual amount, adding up all these records. - Note any notable variations or changes in the amount of septic tank use. 	Regular tracking and documentation of septic tank emptying will enable municipal authorities to input the data into the model, helping to plan and scale sanitation services effectively.
Number of Soak Pit (i.e., not connected to the drain network) Faecal mass flow? (Eqv. Kg/yr)	<ul style="list-style-type: none"> - Record the number of functioning soak pits and estimate the total equivalent mass of diverted faecal matter. - Include observations on the prevalence and condition of soak pits in the area. 	Estimating the faecal mass diverted through soak pits will aid in updating the model and evaluating the effectiveness of existing installations, as well as planning for new ones to reduce direct discharges into drainage systems.

Drain Scraping (kg/yr)	<ul style="list-style-type: none"> - Record drain scraping events, noting the mass of faecal matter removed and therefore not reaching the outlet. - Compile these records to ascertain the annual total in kilograms. - Document any local practices or challenges related to drain scraping. 	Utilizing data on the mass of faecal matter removed from drains in the model will enhance city-wide drain maintenance protocols, preventing blockages and overflows that pose urban flooding and public health risks.
Commercial Areas Contribution (Eqv. Kg/yr)	<ul style="list-style-type: none"> - Calculate equivalent faecal mass contribution from commercial areas in kilograms per year. - Note the density and type of commercial activities in the ward. 	Including accurate data on faecal contributions from commercial areas in the model will inform targeted faecal management strategies, optimizing resource allocation and interventions.
Buildings with No Toilet (Eqv. Kg/yr)	<ul style="list-style-type: none"> - Assess the number buildings lacking toilet facilities and estimate the equivalent faecal mass not entering the drain. - Observe and note any relevant socio-economic or infrastructural factors. 	Identifying and quantifying faecal output from buildings without toilets in the model will help better characterize the spatial variability of faecal production and support targeted management strategies.

5.6.4 Integrating SanIFFlow with existing management system

SanIFFlow approach offers a flexible framework that has the potential to transform the management of urban sanitation. It offers the flexibility to operate at multiple granularities, from the building level to the ward level, accommodating the existing management system of the city corporations. An example has been

shown for RCC (Bari & Kabir, 2023), applying SanIFFlow at the ward level. This approach offers the flexibility to be implemented in similar cities.

The organisational chart of RCC, referred to in Figure 5.3 (Bari & Kabir, 2023), demonstrates a helpful environment for the data-driven methodology that SanIFFlow advocates. The Chief Conservancy Officer, supported by the Deputy Chief Conservancy Officer, can ensure the seamless adoption of SanIFFlow, aligning it with strategic city planning and monitoring. This shift to a proactive, data-informed sanitation management system, enabled by SanIFFlow, will allow the RCC to anticipate and address issues. For example, by identifying drains prone to blockages due to sludge accumulation, they can implement regular maintenance or preventative measures in upstream areas, thereby avoiding potential problems.

Central Supervisors and Conservancy Inspectors are predicted to play a critical role in the collection of detailed, ward-specific data on faecal management attributes, as detailed in Table: 5.1. This data is not only crucial for the success of the model but also instrumental in depicting the spatial variability of faecal production and movement. Such insights will facilitate the transition to proactive sanitation management, emphasised by regular monitoring and targeted maintenance work.

The proposed Data Management and Analytical Unit, which would be part of the Monitoring branch, will be processing this data and producing actionable insights for infrastructure investment prioritisation and service improvements. This unit will enable RCC to visualise the sanitation landscape of the city systematically, leading to well-informed, strategic decision-making.

To realise the full potential of SanIFFlow, we encourage RCC to initiate pilot programs, coupled with rigorous evaluations, to refine the approach and evaluate its scalability. Such pilot studies will inform the broader applicability of the model to other urban settings, potentially transforming sanitation management across various scales. Stakeholder involvement is vital in refining SanIFFlow. We propose the development of communication platforms that enable residents to

report septic tank maintenance, this resident-sourced data will enrich the RCC's direct service records, providing a comprehensive dataset for SanIFFlow.

We invite urban planners, sanitation experts, and policymakers to engage with the SanIFFlow model, not only as a theoretical framework but as a practical tool for strategy development. By employing SanIFFlow, the academic and professional communities can collaboratively foster a new era of sanitation management—proactive, data-driven, and grounded in spatial analytics for public health and environmental sustainability.

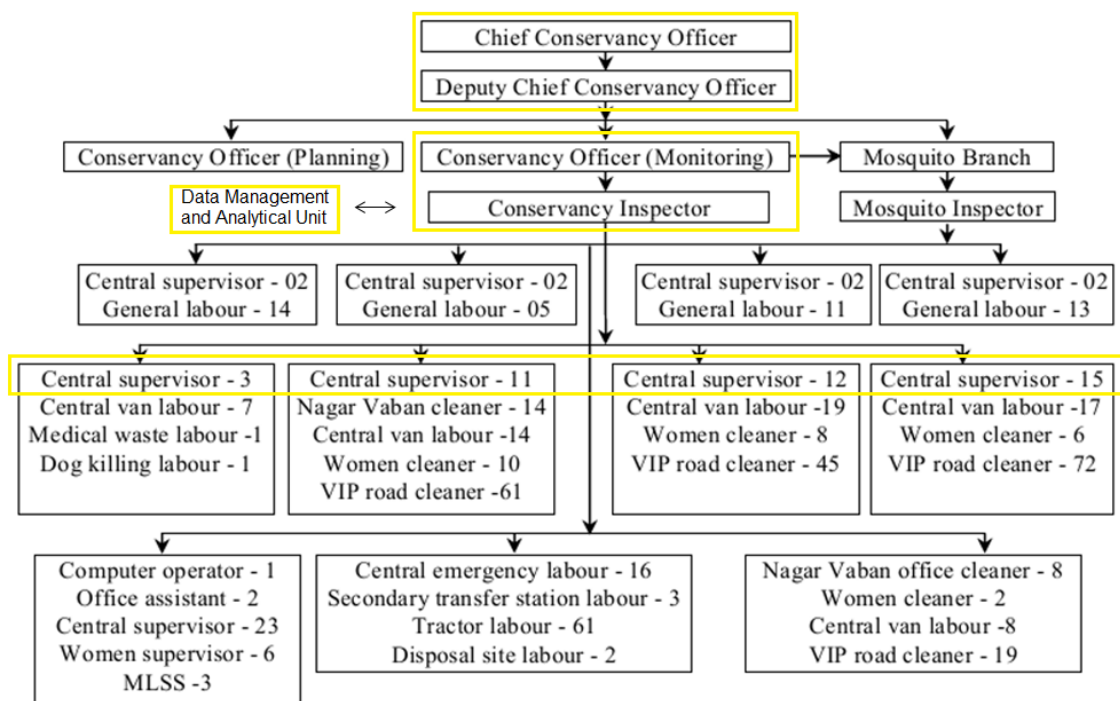


Figure 5.3: Flow diagram of current conservancy department at Rajshahi city using as an example (Bari & Kabir, 2023). The proposed involved levels within the organogram are indicated by yellow boxes.

5.6.5 Limitation and future considerations

Upscaling inherently limits the ability to address local heterogeneities, as data at a larger scale tends to homogenize the diversity observed at a smaller scale (Vandenbulcke & Barth, 2019). Upscaling from the household level to the ward level involves making assumptions, and each of these carries associated uncertainties. The most significant assumption is that building-level data can be

used to represent ward-level behaviours. However, there is a risk that this could oversimplify or misrepresent the diversity of sanitation practices and faecal movement patterns at ward level. It is also likely that certain variables impacting faecal matter flow from the buildings (e.g., septic tank emptying, or use of soak pit) are not represented in ward-level representation. These assumptions and the uncertainties they introduce must be acknowledged and, where possible, quantified in the future research.

Our reliance on open-source data, such as the LandScan population estimates, demonstrates a practical approach to urban faecal production modelling. Despite occasional inaccuracies (Leyk et al., 2019), as evidenced in one case where population data was overestimated, this methodology presents a viable framework for cities lacking detailed local sanitation data. The focus remains on the adaptability and applicability of SanIFFlow approach, which allows for corrections and refinements, emphasising its utility in urban sanitation planning, particularly in similar contexts lacking precise local data. The robustness of this methodology, in light of these limitations, offers a significant contribution to the field of urban sanitation planning and management

5.7 Conclusion

This research presented a city-scale modelling approach to identify an applicable spatial scale for urban sanitation planning aligned with municipal capacities, with a specific focus on the Western Catchment area of Rajshahi city. It establishes a critical link between population density and the production and accumulation of faecal matter.

The proposed SanIFFlow approach, deploying building-level data with ward-level analysis within a city-scale perspective, advances our understanding of faecal movement within urban environments. By capturing both infrastructural attributes, such as sources of faecal production and movement pathways, and the aspects of flow accumulation, it provides an adaptable tool for urban sanitation management. The SanIFFlow model's flexibility across different scales, from individual buildings to wards, enhances its practical applicability in diverse unsewered urban contexts.

The study emphasises the potential of the SanIFFlow model in transforming urban sanitation management. Its adaptability and data-driven nature would align well with current administrative structures, potentially making it a valuable tool for strategic decision-making. The study encourages stakeholder engagement and pilot programmes to refine the model further, ensuring its scalability and effectiveness in other urban settings.

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References

- Bari, M. N., & Kabir, M. R. (2023). *Urban Sanitation Facilities and Its Management in Rajshahi City Urban Sanitation Facilities and Its Management in Rajshahi City*. November.
- Bari, N., Bushra, A., & Zaman, J. (2018). Management of faecal sludge by rajshahi city corporation. *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development*, July, 1–11. http://www.iccesd.com/proc_2018/Papers/r_p4803.pdf
- Dissanayake et al. (2007) *Baseline Water Quality Survey for Rajshahi, Bangladesh, WASPA Asia: Project Report 7*.
- Gambrill, M., Gilsdorf, R. J., & Kotwal, N. (2020). Citywide Inclusive Sanitation—Business as Unusual: Shifting the Paradigm by Shifting Minds. *Frontiers in Environmental Science*, 7(February), 1–10. <https://doi.org/10.3389/fenvs.2019.00201>
- Hawkins, P., & Muxímpua, O. (2015). Developing Business Models for Fecal

- Sludge Management in Maputo. In *Water and Sanitation Program* (Issue June). <https://wsp.org/sites/wsp.org/files/publications/WSP-Developing-Business-Models-for-Fecal-Sludge-Management-Maputo.pdf>
- Kelkar, V., & Seetha Ram, K. (2019). a Literature Review Evaluating New Approaches To Resolving the Sanitation Challenge in Developing Asia. In *ADB Working Paper Series* (Issue 976). <https://www.adb.org/publications/evaluating->
- Leyk, S., Gaughan, A. E., Adamo, S. B., de Sherbinin, A., Balk, D., Freire, S., Rose, A., Stevens, F. R., Blankespoor, B., Frye, C., Comenetz, J., Sorichetta, A., MacManus, K., Pistolessi, L., Levy, M., Tatem, A. J., & Pesaresi, M. (2019). The spatial allocation of population: a review of large-scale gridded population data products and their fitness for use. *Earth System Science Data*, 11(3), 1385–1409. <https://doi.org/10.5194/essd-11-1385-2019>
- Lüthi, C., Willetts, J., & Hoffmann, S. (2020). Editorial: City-Wide Sanitation: The Urban Sustainability Challenge. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.585418>
- Mtika, W. M., & Tilley, E. (2020). Environmental Sanitation Planning: Feasibility of the CLUES Framework in a Malawian Small Town. *Frontiers in Environmental Science*, 7. <https://doi.org/10.3389/fenvs.2019.00204>
- Niwagaba, C. B., Mbéguéré, M., & Strande, L. (2014). Faecal Sludge Quantification, Characterisation and Treatment Objectives. In L. Strande, M. Ronteltap, & D. Brdjanovic (Eds.), *Faecal Sludge Management Systems Approach for Implementation and Operation* (pp. 19–44). IWA Publishing.
- Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., Schoebitz, L., Scott, R., Sleigh, A., Strande, L., & Veses, O. (2020). Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned From a Global Implementation of Excreta-Flow Diagrams. *Frontiers in Environmental Science*, 8, 1. <https://doi.org/10.3389/fenvs.2020.00001>

- Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2014). Fecal sludge management (FSM): analytical tools for assessing FSM in cities. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 371–383. <https://doi.org/10.2166/washdev.2014.139>
- Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Critical Reviews in Environmental Science and Technology*, 45(17), 1827–1879. <https://doi.org/10.1080/10643389.2014.1000761>
- Schmidt, M. (2008). The Sankey Diagram in Energy and Material Flow Management. *Journal of Industrial Ecology*, 12(2), 173–185. <https://doi.org/https://doi.org/10.1111/j.1530-9290.2008.00015.x>
- Schrecongost, A., Pedi, D., Rosenboom, J. W., Shrestha, R., & Ban, R. (2020). Citywide Inclusive Sanitation: A Public Service Approach for Reaching the Urban Sanitation SDGs. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00019>
- Scott, P., & Cotton, A. P. (2020). The Sanitation Cityscape – Toward a Conceptual Framework for Integrated and Citywide Urban Sanitation. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00070>
- Scott, P., Cotton, A., & Sohail, M. (2015). Using tenure to build a “sanitation cityscape”: narrowing decisions for targeted sanitation interventions. *Environment and Urbanization*, 27(2), 389–406. <https://doi.org/10.1177/0956247815569415>
- Sultana, M. S., Waine, T., Bari, N., & Tyrrel, S. (2023). Towards a new spatial representation of faecal sources and pathways in unsewered urban catchments using open-source data. *Journal of Water, Sanitation and Hygiene for Development*, 13(4), 289–300. <https://doi.org/10.2166/washdev.2023.227>

- Tabassum, S. (2020). Drainage system, its water quality and health effect: A case study of Rajshahi city, Bangladesh. *Scientific Journal of Environmental Sciences*, 9(1), 323–336. <https://doi.org/10.14196/sjes.v9i1.2612>
- Vandenbulcke, L., & Barth, A. (2019). Upscaling of a local model into a larger-scale model. *Ocean Science*, 15(2), 291–305. <https://doi.org/10.5194/os-15-291-2019>
- Willettts, J., Mills, F., & Al'Afghani, M. (2020). Sustaining Community-Scale Sanitation Services: Co-management by Local Government and Low-Income Communities in Indonesia. *Frontiers in Environmental Science*, 8. <https://doi.org/10.3389/fenvs.2020.00098>

6 DISCUSSION AND CONTRIBUTION TO KNOWLEDGE

6.1 Synthesis

An innovative geospatial modelling approach has been developed to address the immense yet under-explored challenge of understanding complex urban sanitation systems, particularly in unsewered cities. The research offered low-cost, sanitation mapping to fill numerous data gaps and promote proactive management through the novel integration of open-source spatial data. In addition, uncertainty and sensitivity analysis provided the challenges of modelling the system. Validating fieldwork affirmed the broad reliability of the methodology while revealing needs for complementary empirical data. Testing an up-scaled model identified key considerations around the practical spatial scale for decision-making. Collectively, the research generated vital contribution to theory and practical tools to enhance public health through improved sanitation planning.

This chapter discusses the objectives and how they contributed to achieving the overall aim of the thesis (Figure 6.1).

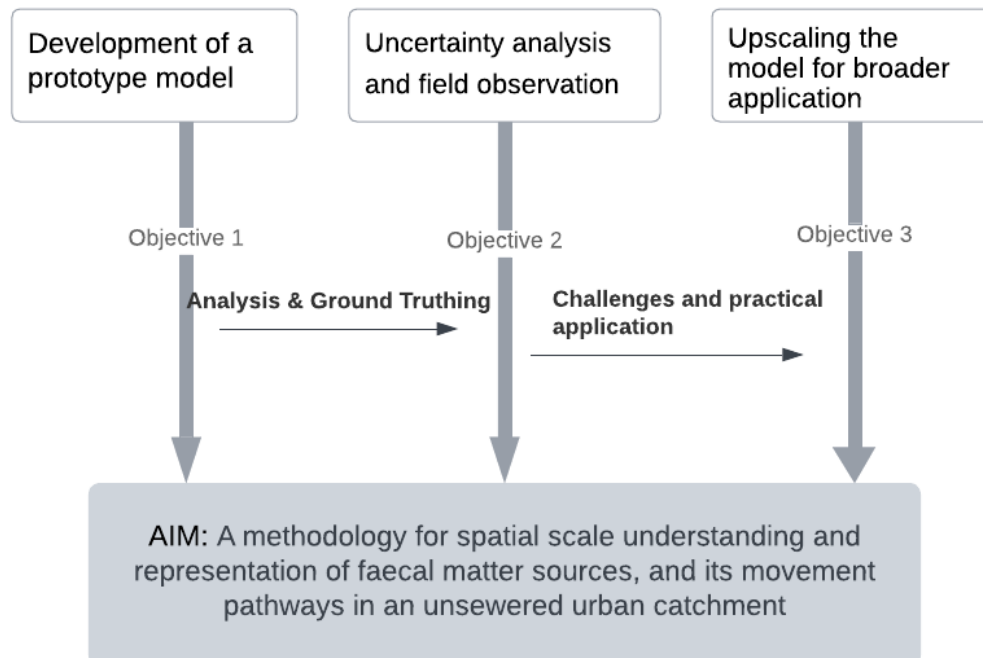


Figure 6.1: The overall aim of the research is achieved through a structured journey: from initial prototype modelling and real-world validation, to the eventual upscaling for comprehensive urban catchment applications using open-source data.

6.1.1 Objective 1:

To develop a prototype methodology for mapping faecal sources, pathways and receptors in a small sub-catchment

The critical issue of insufficient sanitation infrastructure data in cities of the developing world has long served as an impediment to evidence-based management strategies. Traditionally, this deficiency has been caused by limited monitoring and spatial analysis capabilities. However, this thesis introduces a novel approach that capitalises on the untapped resources of open-source spatial data. The methodology was created to map faecal matter production and movement pathways in unsewered cities by combining freely available building footprint data, gridded population statistics, and digital elevation models (DEM).

This methodology is innovative in its application rather than its individual components. For instance, building footprint and gridded population data have been utilised extensively in various fields such as examine patterns of poverty, model traffic patterns, changes in land use (Leyk et al., 2019) but remain unexplored in sanitation mapping. The concept of average faecal matter production per individual was introduced here, allowing for building-wise faecal production estimates (Peal et al., 2014; Strande et al., 2018). By assigning population counts to specific buildings, and linking these to drainage networks through proximity analysis, a spatial representation of faecal mass flow was achieved. Moreover, this approach filled the void where empirical data had previously been absent, serving as a proof-of-concept for the utility of open geospatial data in bridging this massive data gap.

A significant feature of this methodology lies in the adaptation of existing techniques for new applications. For example, while the use of DEM data to calculate building heights is not new and is often performed using LIDAR technology (Zeng et al., 2014), this thesis introduces a novel twist. Ground elevation was extracted from DEM data by applying a specific set of rules: using the minimum elevation within a 100-metre radius where there were more than 12 data points, which is likely to represent ground elevation. This ground elevation data, mapped at a 100-metre resolution, was then used to calculate building height.

Additionally, the ground elevation data served an additional purpose by informing the flow direction of storm drains. In cities like Rajshahi, the storm drainage systems are

gravity-driven, aligning with natural topographical gradients. This ground elevation data provides a consistent and reliable basis for determining the flow directions, adhering to established natural gradients (Li et al., 2020). In doing so, the research addressed two significant gaps:

Lack of granular spatial data on sanitation infrastructure:

Traditional methods of collecting sanitation data often depend on aggregated, city-wide data, which fails to capture the complex spatial variations necessary for targeted interventions (Peal et al., 2014, 2020). While previous efforts have ventured into household-level surveys (Whittington et al., 1993) or smaller geographical representations via SFD (Hawkins & Muxímpua, 2015), such approaches have been resource-intensive and logistically impractical at larger scales. Similarly, a modelling of faecal pathogen flows has been shown to be effective for a street level, but do not extend well to broader urban or catchment areas, leaving a significant gap in our understanding of faecal matter movement (Foster et al., 2021). The importance of spatial granularity in this context has been emphasised by Mills et al. and (Peal et al., 2020), as well as in the work of Foster et al., who highlighted the unknown offsite risks arising from a lack of hydrological catchment-based data.

Addressing this gap, the present study employs a novel approach that models faecal matter production and movement at the level of individual buildings, connecting these outputs to drainage networks within a hydrological catchment. This detailed spatial resolution enables an understanding of how risk in one area, particularly upstream, can influence conditions in other parts of an urban catchment. This research is unique in that it makes use of publicly available data, recognises the need for a spatial understanding of faecal movement and sanitation infrastructure in places with limited resources, and allows for potential global applicability. By doing this, the methodology not only addresses the particular issues mentioned above but also offers a scalable and accessible way to plan for sanitation in places where data are extremely limited.

Absence of low-cost, spatial mapping techniques:

Detailed spatial sanitation data has been nearly impossible to obtain in secondary cities due to lack of monitoring or record keeping. This study demonstrated the vast potential of open geospatial data for low-cost sanitation mapping to fill the data gaps.

Freely available data on buildings, population and elevation was innovatively integrated to approximate infrastructure and faecal mass production. In urban settings, the usual approach for estimating faecal generation relies on utilising the average mass of waste produced per person per day, which is then multiplied by the number of individuals who excrete daily (Rose et al., 2015; Strande et al., 2014). Here, population attributed to buildings according to building volume (e.g., LandScan population data and OpenStreetMap) used to characterise the spatial variability of faecal production.

However, it is important to note the existence of uncertainties, particularly concerning the representation of complex real-world dynamics of faecal production, their release in the environment and movement that lack empirical validation. It is known that building volume estimated using DEM & GIS data could lead to erroneous attribution of population to buildings while LandScan population data has also its own limitations causing mismatch of spatial alignment with real world census data (Leyk et al., 2019; Zeng et al., 2014). The detailed characterisation of these uncertainties falls beyond the scope of this objective; however, an in-depth examination of uncertainties stemming from various assumptions is undertaken to address this in chapter 2. Although the methodology represents a significant step forward, it is essential to acknowledge the limitations inherent in any modelling approach that attempts to mimic intricate real-world systems (Saltelli et al., 2020). Given that this methodology is pioneering in its application of these particular data sets for sanitation planning the limitations discussed herein serve not only as caveats for the present study but also as focal points for refinement in future research efforts.

Overall, this foundational methodology pioneered a novel integration of open-source data with a city's drainage data to map faecal sources, production, and pathways with spatial specificity at a scale aligning with on-site sanitation management. This proof-of-concept developed a foundation for adapting and improving spatial sanitation planning in the contexts of data scarcity.

6.1.2 Objective 2:

Addressing and assessing the uncertainty of the spatial pattern of faecal production and movement

The methodology developed in Chapter 2 relies on several assumptions, introducing a level of uncertainty into the patterns of faecal matter flow. This study identifies factors contributing to the spatial variability of faecal matter flow, building on the findings of previous research (Bari, 2017; Mills et al., 2018; Strande et al., 2018; Tabassum, 2020). Traditional approaches to understanding these patterns have largely been rooted in either modelling or field studies (Foster et al., 2021; Peal et al., 2014; Strande et al., 2018). Field studies, although informative, are infrequent and lack a focused investigation into the city's hydrological conditions, a critical determinant of spatial variability as pointed out by some localised studies (M. N. Bari, 2017; Li et al., 2020; Tabassum, 2020). Variability in faecal production and movement across unsewered cities arises from diverging population densities and hydrological conditions. Furthermore, there has been no established methodology for simulating sanitation systems on a spatial scale considering urban hydrology.

It's worth emphasising that the issue of spatial variability isn't limited to the current study area, Rajshahi; it has worldwide implications, as evidenced by the Peal et al (2020) study including 39 cities. Previous research has certainly shown interest in the spatial variability of faecal production (Peal et al., 2014), but it has yet to address it on the spatial scale presented in this work. Even though earlier studies may have employed field-based interviews, scaling these insights remains a significant challenge including how various factors at spatial scale influence the faecal movement

These factors are addressed and characterised in Chapters 3-4. It highlights five factors that influence faecal matter flow in unsewered cities, which includes the emptying of septic tanks, the use of soak pits, and sludge removal from drains, variations in faecal matter production by building types, and the presence or absence of toilets.

These five influencing factors were tested with different scenarios, which revealed how small factors can significantly impact outcomes when integrated spatially. For instance, changing assumptions about septic tank emptying quantities significantly impacted faecal movement mapping.

By interrogating how small details translate into significant spatial impacts, this chapter addressed a key gap around understanding inherent system complexity and unpredictability. Previous studies had acknowledged the limitation in sanitation data in

spatial perspectives (Kelkar & Seetha Ram, 2019; Strande et al., 2018). This study relied on simulated data for spatial representation of indicative scenarios, empirical data was needed to truly minimise and understand the uncertainties.

The 4th chapter helped to fill this gap partially through fieldwork, combining observations, interviews and focus groups discussion to validate the spatial modelling approach. Findings showed a reasonable agreement between modelled and observed drain directions, affirming broad reliability. This ground-truthing addressed a significant knowledge gap around lack of validation and evidence-based improvement of sanitation models (Peal et al., 2014). The mixed methods, i.e., modelling and follow up field study, provided a robust template for strengthening modelling, revealing spatial and thematic areas needing empirical data integration. Therefore, the study highlighted the needs for implemented level of spatial scale in chapter 5, which can be incorporated in practical use of sanitation management system.

Both chapters demonstrated the importance of applying spatial perspectives to advance the understanding of urban sanitation landscape. The analysis of uncertainty and subsequent validation, when examined within a specific local context and represented through mapping, have provided fresh insights into enhancing the efficiency of these intricate systems. It was intriguing to see how each of the factors individually remain insignificant but in combination play a vital role in the spatial movement of faecal flow at catchment level. They emphasised importance of empirical, multi-scalar and systems-based perspectives to elucidate this complex challenge (Scott et al., 2015). By integrating uncertainty interrogation with high-resolution spatial mapping, this research enabled new systems-based insights into sanitation complexity.

6.1.3 Objective 3:

To identify and resolve the challenges of upscaling by applying the prototype methodology to a large urban catchment

In Chapter 5, the study addresses the objective of identifying and resolving challenges linked to the scaling up of spatial models. The prototype model developed in Chapters 2-4 revealed two principal issues: first, the current operational system is not equipped to accommodate the granularity of building-level service delivery; and second, there

is a need for a scale, capable of capturing ongoing operating data for proactive service maintenance. To address these issues, an up scaled ward-level model was developed, aligning with municipal boundaries and the scale of local operations.

The up scaled method also mitigates uncertainties tied to population allocation at the building level. These uncertainties arise when attributing population to buildings based on volume, a practice prone to error. However, aggregating several buildings can reduce such inaccuracies by averaging out the influence of buildings volume, a source of error as indicated by Fisher (1997), Zeng et al. (2014), and Grosz et al. (2017).

Up-scaling studies frequently rely on coarsely resolved spatial input data for two primary reasons: the unavailability of fine-resolution data or limited computational capacity. In this study, however, the driving factor was neither; instead, the focus was on aligning the model with the service delivery scale, as discussed by Willetts, Mills and Al'Afghani (2020). While upscaling did reduce errors in representing faecal production at the building level. The prototype model, focused on sub-catchments, preserved local intricacies, whereas the ward-level model facilitated broader applicability. The chapter enhanced prior work that was limited to either local scales or city-wide (Foster et al., 2021; Peal et al., 2014; Whittington et al., 1993), highlighting the necessity for multi-scalar sanitation modelling (Scott & Cotton, 2020).

The study advances the field of multi-scalar spatial modelling for urban sanitation by addressing key issues such as the importance of integrating monitored data, the effects of data aggregation, and the trade-offs between granularity and scalability. It also adapts the model to better align with municipal governance structures, thereby enhancing its practical applicability. Moreover, the study emphasized the need to integrate monitored data at appropriate scales to reduce uncertainties, addressing gaps in the existing literature which has often relied excessively on model assumptions without empirical validation (Peal et al., 2014).

The research acknowledged the limitation and flagged it as an area requiring further investigation, drawing parallels to methods used in agro-environmental assessments (Folberth et al., 2016). In terms of technical details,

Loss of Spatial Heterogeneity: Aggregating data can result in a loss of spatial heterogeneity. The study identifies this issue as a priority for future research.

Uncertainties in Drainage Aggregation: The study introduces potential uncertainties when it comes to aggregating drainage systems. Specifically, the cleaning of lower-order drains may not impact higher-order drains in the way the model suggests, a complexity that the study itself flags for further investigation.

Overall, the study significantly refined the robustness and policy relevance of spatial modelling for urban sanitation planning. It tackled various challenges linked to scale optimisation, but also highlighted remaining gaps, especially in relation to the need for more flexible, empirically verified models. These lingering issues are critical to address in future work, particularly if the goal is to provide policy-relevant insights without compromising crucial local details.

6.2 Contribution to knowledge

This research makes several key contributions across the domains of methodology, empirical evidence, theoretical knowledge, and knowledge of practice relating to faecal sludge management in unsewered urban areas (Table 6.1). Unlike traditional city-level approaches to sanitation, this research addresses a critical gap by offering localised, spatial insights with potential for effective planning and management.

Methodologically, the research employs a unique combination of spatial analysis to develop a model, the evaluation and characterisation of the uncertainties of the model assumptions, and the use of fieldwork for checking and model improvement. This well-rounded approach is especially beneficial in data-scarce environments, enriching both the understanding of sanitation infrastructure and the tracking of faecal matter in urban settings.

The study proposes a new method for spatial representation of faecal matter sources and movement pathways using open-source data, as demonstrated through the case study in Rajshahi, Bangladesh (Chapter 2). Building upon this, the research critically evaluates the uncertainties associated with the model's assumptions in Chapter 3. The analysis identifies those influencing factors that are considered most likely to affect the variability in spatial pattern of faecal matter production and movement pathways. In Chapter 4, fieldwork illustrates the potential and constraints of open-source data and reveals new insights from direct observation, informal conversation with professionals and focus group discussion. For example, the city corporation employs a team to

manage the drainage systems through sludge scraping and removal (which is a previously unreported faecal sludge export path from the city catchment). This challenged one of the model's assumption that all generated faecal matter reaches the catchment outlet. Also, drain sludge often ends up on the roads after floods, leaving a layer of dark grey muddy residue that may then lead to contamination through other routes. The insights provided not only underline the capabilities of such a model but also highlight potential challenges, thereby offering pragmatic solutions for enhancing their application in various contexts.

Mapping the sanitation system is important for understanding the burden of sanitation infrastructure, the distribution of unsafely managed faecal matter into the environment, and the fate of faecal matters in un-sewered systems (Peal et al., 2020; Strande et al., 2018). The spatial analysis of faecal matter flow, is a component that the World Bank's City-Wide Inclusive Sanitation (CWIS) has yet to investigate and incorporate. It aligns with unmet need of (CWIS) establishing clear metrics and data collection processes, redesigning financing and incentives, integrating CWIS principles into policies and regulations (Gambrill et al., 2020; Strande et al., 2021). The research also resonates with environmental justice theories, highlighting the disproportionate impact of poor sanitation on low-income communities (Amin et al., 2020). By offering a spatial lens to understand faecal matter distribution, this work serves as a tool for equitable service delivery and targeted public health interventions. Thus, the study not only fills gaps in existing literature but also adds academic understanding and practical value.

Regarding practice-oriented knowledge, a key highlight is the development of a ward-level framework and intuitive visualisation for context-specific sanitation planning (Chapter 5). The ward-level analysis aligns with governance structures and generates actionable insights. This demonstrates the value of engaging with practitioners in developing relevant planning approaches.

Collectively, these contributions combine around the central theme of spatial faecal matter management in unsewered urban settings, offering a holistic approach to sustainable development in this crucial area. In future research these contributions can be used to support sanitation interventions as well as public health research like wastewater surveillance, risk assessment, and disease dynamics.

Table 6.1: Contribution to knowledge. A reference to chapters for each has been made.

Domain of Contribution	Extent of contribution		
	What has been developed	What has been confirmed	What has advanced knowledge
Methodology	<ul style="list-style-type: none"> A methodology for spatial understanding of sanitation status in unsewered urban catchment (All chapters) 		
Empirical evidence	<ul style="list-style-type: none"> A new spatial representation of faecal sources-pathways in unsewered urban catchments using open-source data (Chapter 2) An analysis of factors that influence the spatial pattern of faecal matter flow in unsewered cities (Chapter 3) Open-source data used for spatial scale characterisation of urban sanitation infrastructure - a field study in Rajshahi, 	<ul style="list-style-type: none"> The study confirms known challenges around lack of sanitation infrastructure data and spatial understanding of faecal flows in cities like Rajshahi (Chapter 2). The study confirms the challenges in representing real-world faecal waste flows in data-scarce contexts (Chapter 3). 	<ul style="list-style-type: none"> It advances knowledge by demonstrating an approach to create a spatial representation of faecal sources and pathways using open-source data (Chapter 2). The work offers both scientific and practical insights into the challenges of managing urban sanitation in resource-constrained contexts, serving as a foundation for subsequent research and policy interventions (Chapter 3). The fieldwork output enriched spatial understanding of urban

	<p>Bangladesh (Chapter 4)</p> <ul style="list-style-type: none"> Criteria for a parsimonious representation scale for faecal management in unsewered urban areas (Chapter 5) 	<ul style="list-style-type: none"> Open-source data can be used for spatial representation in unsewered urban areas (Chapters 2 & 4) The study confirms the development of models that can capture broader patterns and trends in faecal matter flow across the city (Chapter 5). The study also can provide insights for urban planning for sanitation management. A ward-level model can help identify wards with particularly problematic sanitation issues, thereby guiding targeted interventions (Chapter 5). 	<p>sanitation, bridging research gaps and guiding future academic and practical efforts (Chapter 4).</p> <ul style="list-style-type: none"> The key knowledge advances are in the demonstration of upscaling techniques and alignment with governance structures, while the confirmation lies in reiterating the need for a tailored spatial scale and integrated data-driven approach for practical sanitation management (Chapter 5).
Theoretical Knowledge	<ul style="list-style-type: none"> An understanding of the spatial characteristics of faecal matter 		<ul style="list-style-type: none"> To inform future sanitation interventions as well as public health research like

	sources and its movement in unsewered urban catchments (All chapters)		wastewater surveillance, risk assessment, and disease dynamics.
Knowledge of practice	<ul style="list-style-type: none"> The key knowledge of practice relates to providing both a practical framework using ward-level data and an intuitive visual tool to guide context-specific sanitation planning and management in a proactive manner (Chapter 5). 		

6.3 Limitation of the research

While generating important innovations, this thesis also faced some key limitations:

- Reliance on assumptions due to absence of empirical data: Many model parameters depended on assumptions that require ground-truthing through intensive field studies.
- Single case study area: The research was restricted to Rajshahi, limiting generalizability. Testing across diverse urban contexts is needed.
- Static modelling approach: The models represented snapshots rather than dynamic processes evolving over time. Capturing temporal changes is an area for improvement.

- Coarse validation metrics: Validation relied more on qualitative than quantitative metrics. Precise statistical validation could better characterize uncertainties.
- Pilot-scale application: The models were not implemented for real-world planning, limiting understanding of on-ground impacts and challenges.
- Insufficient policy linkages: Engagement with city stakeholders was limited, resulting in potential mismatches with actual policy needs and capacities.

Addressing these limitations through multi-city model implementations, quantitative uncertainty characterization, dynamic calibration, and extensive stakeholder engagement will strengthen research outcomes and real-world impacts. Overall, this thesis provided an important foundation and proof-of-concept upon which future work can build to advance spatial modelling as a decision-support tool for transforming urban sanitation planning and management.

6.4 Conclusions and Future Directions

This thesis produced critical innovations in spatial modelling for urban sanitation planning and management through an evolving method of developing a prototype methodology, assessing uncertainties, conducting fieldwork for validating and identifying areas for improvement, and finally scaling to adjust for current needs. The methodology pioneered the use of open-source data to map faecal production, sources, and movement pathways with unique spatial specificity in areas where empirical data was significantly insufficient. Sophisticated uncertainty analysis gave critical insights into sanitation systems' sensitive dependency and rising complexity. Validating fieldwork affirmed broad reliability of the spatial modelling approach while revealing crucial needs for complementary empirical data to capture localised intricacies. Testing an up scaled ward-level model highlighted key trade-offs between spatial detail and practical alignment with governance constraints.

Collectively, the research constituted vital progress in overcoming spatial multi-scalar modelling to bridge gaps between building-level granularities and entire city's aggregated coverage supporting coherent planning.

Moving forward, this thesis provides a crucial foundation for advancing spatial modelling to fill persistent data gaps and better elucidate the dynamics of urban sanitation systems. Continued methodological refinement, granular empirical data integration, multi-scalar troubleshooting, and alignment with policy needs will further enhance modelling robustness, accessibility, and real-world implementation. Harnessing spatial perspectives and open-source data has the potential to drive progress on sanitation management as a complex socio-technical challenge fundamentally affecting public health and environmental sustainability. The innovations generated in this thesis represent important steps on that pathway which must continue to be paved collectively.

References

- Amin, N., Liu, P., Foster, T., Rahman, M., Miah, M. R., Ahmed, G. B., Kabir, M., Raj, S., Moe, C. L., & Willetts, J. (2020). Pathogen flows from on-site sanitation systems in low-income urban neighborhoods, Dhaka: A quantitative environmental assessment. *International Journal of Hygiene and Environmental Health*, 230, 113619. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113619>
- Bari, M. N. (2017). Study on Existing Faecal Sludge Management Situation in Rajshahi Rajshahi City. *Proceedings of the WasteSafe 2017 – 5th International Conference on Solid Waste Management in South Asian Countries 25-27 February 2017, Khulna, Bangladesh STUDY, March*.
- Foster, T., Falletta, J., Amin, N., Rahman, M., Liu, P., Raj, S., Mills, F., Petterson, S., Norman, G., Moe, C., & Willetts, J. (2021). Modelling faecal pathogen flows and health risks in urban Bangladesh: Implications for sanitation

- decision making. *International Journal of Hygiene and Environmental Health*, 233, 113669. <https://doi.org/https://doi.org/10.1016/j.ijheh.2020.113669>
- Gambrill, M., Gilsdorf, R. J., & Kotwal, N. (2020). Citywide Inclusive Sanitation—Business as Unusual: Shifting the Paradigm by Shifting Minds. *Frontiers in Environmental Science*, 7, 1–10. <https://doi.org/10.3389/fenvs.2019.00201>
- Hawkins, P., & Muxímpua, O. (2015). Developing Business Models for Fecal Sludge Management in Maputo. In *Water and Sanitation Program* (Issue June). <https://wsp.org/sites/wsp.org/files/publications/WSP-Developing-Business-Models-for-Fecal-Sludge-Management-Maputo.pdf>
- Kelkar, V., & Seetha Ram, K. (2019). a Literature Review Evaluating New Approaches To Resolving the Sanitation Challenge in Developing Asia. In *ADB Working Paper Series* (Issue 976). <https://www.adb.org/publications/evaluating->
- Leyk, S., Gaughan, A. E., Adamo, S. B., de Sherbinin, A., Balk, D., Freire, S., Rose, A., Stevens, F. R., Blankespoor, B., Frye, C., Comenetz, J., Sorichetta, A., MacManus, K., Pistolessi, L., Levy, M., Tatem, A. J., & Pesaresi, M. (2019). The spatial allocation of population: a review of large-scale gridded population data products and their fitness for use. *Earth System Science Data*, 11(3), 1385–1409. <https://doi.org/10.5194/essd-11-1385-2019>
- Li, C., Fan, Z., Wu, Z., Dai, Z., Liu, L., & Zhang, C. (2020). Methodology of sub-catchment division considering land uses and flow directions. *ISPRS International Journal of Geo-Information*, 9(11). <https://doi.org/10.3390/ijgi9110634>
- Mills, F., Willetts, J., Petterson, S., Mitchell, C., & Norman, G. (2018). Faecal pathogen flows and their public health risks in urban environments: A proposed approach to inform sanitation planning. *International Journal of Environmental Research and Public Health*, 15(2). <https://doi.org/10.3390/ijerph15020181>

- Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., Schoebitz, L., Scott, R., Sleight, A., Strande, L., & Veses, O. (2020). Estimating Safely Managed Sanitation in Urban Areas; Lessons Learned From a Global Implementation of Excreta-Flow Diagrams. *Frontiers in Environmental Science*, 8, 1. <https://doi.org/10.3389/fenvs.2020.00001>
- Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2014). Fecal sludge management (FSM): analytical tools for assessing FSM in cities. *Journal of Water, Sanitation and Hygiene for Development*, 4(3), 371–383. <https://doi.org/10.2166/washdev.2014.139>
- Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Critical Reviews in Environmental Science and Technology*, 45(17), 1827–1879. <https://doi.org/10.1080/10643389.2014.1000761>
- Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Espeland, W., Kay, J., Lo Piano, S., Mayo, D., Jr, R., Portaluri, T., Porter, T., Puy, A., Rafols, I., Ravetz, J., Reinert, E., Sarewitz, D., Stark, P., & Vineis, P. (2020). Five ways to ensure that models serve society: a manifesto. *Nature*, 582, 482–484. <https://doi.org/10.1038/d41586-020-01812-9>
- Scott, P., Cotton, A., & Sohail, M. (2015). Using tenure to build a “sanitation cityscape”: narrowing decisions for targeted sanitation interventions. *Environment and Urbanization*, 27(2), 389–406. <https://doi.org/10.1177/0956247815569415>
- Strande, L., Ronteltap, M., & Brdjanovic, D. (2014). *Faecal Sludge Management – Systems Approach for Implementation and Operation*. IWA Publishing. <https://doi.org/10.2166/9781780404738>
- Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B. J., & Niwagaba, C. B. (2018). Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions. *Journal of Environmental Management*, 223(June),

898–907. <https://doi.org/10.1016/j.jenvman.2018.06.100>

- Strande, L., Velkushanova, K., & Brdjanovic, D. (2021). Setting the stage. In B. D. and B. C. Velkushanova K., Strande L., Ronteltap M., Koottatep T. (Ed.), *Methods for Faecal Sludge Analysis* (pp. 1–14). IWA Publishing.
- Tabassum, S. (2020). Drainage system, its water quality and health effect: A case study of Rajshahi city, Bangladesh. *Scientific Journal of Environmental Sciences*, 9(1), 323–336. <https://doi.org/10.14196/sjes.v9i1.2612>
- Whittington, D., Lauria, D. T., Choe, K., Hughes, J. A., Swarna, V., & Wright, A. M. (1993). Household sanitation in Kumasi, Ghana: A description of current practices, attitudes, and perceptions. *World Development*, 21(5), 733–748. [https://doi.org/10.1016/0305-750X\(93\)90030-D](https://doi.org/10.1016/0305-750X(93)90030-D)
- Zeng, C., Wang, J., Zhan, W., Shi, P., & Gambles, A. (2014). An elevation difference model for building height extraction from stereo-image-derived DSMs. *International Journal of Remote Sensing*, 35. <https://doi.org/10.1080/01431161.2014.975375>

APPENDICES

Appendix A Ethical Approval Letter



19 May 2022

Dear Mrs Sultana ,

Reference: CURES/15755/2022

Title: Spatial Representation of Faecal Pollution in an Urban Catchment (fieldwork)

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/15755/2022 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B Modelling Assumptions (Chapter 3)

This is the list of assumptions used in the modelling (Table B-1) described in Chapter 2 and subsequently these assumptions were extensively assessed and analysed in Chapter 3. This also describes the underlying rationale for each assumption and indicates the potential uncertainties linked with that assumption. Furthermore, this also shows the potential ways to test the sensitivities of each assumption.

Table B- 2: List of assumptions used in the modelling. This also describes the underlying rationale for each assumption and indicates the potential uncertainties linked with that assumption. Furthermore, this also shows the potential ways to test the sensitivities of each assumption.

The full table can be found as insert in the following pages 170 - 174.

Table B 1: List of assumptions used in the modelling. This also describes the underlying rationale for each assumption and indicates the potential uncertainties linked with that assumption. Furthermore, this also shows the potential ways to test the sensitivities of each assumption.

Current input assumptions	Justification	Preliminary approach to sensitivity analysis	Current assessment of effect of assumption on model output	Effect (pre-sensitivity analysis)	Scenarios for sensitivity	Approx. Time required for analysis
1. Every building has a toilet and septic tank	The WaterAid SFD lite report suggests that 80% of the city population uses septic tanks with the remainder using lined pits of various designs, some of which are similar to septic tanks. The City Corporation reports no open defecation.	Identify candidate building types / zones that may have no toilet and septic tank and model the impact on the spatial pattern in the map.	The assumption that every building has a septic tank is probably an over-estimate of reality. There will be buildings that do not have a toilet at all. An over-estimate of this type has the effect of spreading faecal sources over a greater number of buildings than may be the actual case in reality, which in theory could increase the apparent faecal flow in parts of the city where in fact there are no toilets, and underestimate the flow in parts of the city where intensity of toilet use is actually higher.	Low	Identifying candidate building types/zones (that may have no toilet and septic tank) needs fieldwork. However, a sensitivity test will be conducted to simulate the influence on the spatial pattern and faecal production, taking into account the following situations. - <ul style="list-style-type: none"> 1% randomly selected building will be excluded (The initial plan is to employ randomised 1% buildings, but if the criteria can be identified, I will use them instead.) 5% randomly selected building will be excluded These two scenarios hopefully will cover range of building without toilet. As currently there is no open defecation it can be confidently assumed to be very low.	2 – Model run for 1% & 5%. Each includes following steps - <ul style="list-style-type: none"> Selection of buildings Network building Faecal mass flow calculation approx... 1 day
2. The centre of the plot was taken as the location of septic tank	It is unknown since the specific location is not set conventionally, some are on the front side of the house, others are on the backside, and some are on one of the sides of the house (Bari, 2017). However, The septic tanks are located within the plot because the plot holder would need to install the tank within their property rather than outside since they have the legal right to build on the plot. As a result, this is a consistent and arbitrary method of allocating a spatial location in the GIS representation. It is necessary to assign a position in the prototype's spatial representation.	The effect of the assumption can be tested by moving the septic tank mean centroid location within the plot.	It will not affect faecal production estimate, but it may affect the faecal movement pathways. If the septic tanks are placed in any other position on the plot, it may result in the plot being attached to another drain and therefore directing the faecal flow to another drain. With a few exceptions, most will have little effect on the outcome because most buildings are positioned adjacent to a drain - the distance may vary depending on the centroid and entry location, but the proximity will be unlikely to be affected by building position in respect to a drain. Septic tanks position cannot be identified by remote sensing but field observation may be useful.	Very low	The septic tank can be placed at any of the four corners or sides of the plots/buildings, even though it is assumed to be in the centre. Moving the position and then connecting it to the nearby drains can increase the sensitivity of the location, allowing us to detect changes in the spatial distribution pattern of faecal mass flow. Although taking reality into account might result in an unlimited number of modelling situations, we decided to see the followings: <ol style="list-style-type: none"> 1. Septic tank is located in the northeast corner 2. Septic tank is located in the northwest corner 3. Septic tank is located in the southeast corner 4. Septic tank is located in the southwest corner 5. Septic tank is located in the middle-north side 6. Septic tank is located in the middle-west side 7. Septic tank is located in the middle-south side 8. Septic tank is located in the middle-west side 	8 – Model run and each one needed to be built separately. Each includes following steps - <ul style="list-style-type: none"> Moving location points Proximity analysis Creating service line Network building Faecal mass flow calculation Tedious work – approx... 2 -weeks (this is still under discussion)
3. All septic tanks are connected to the drains rather than a soakaway	WaterAid (2018) estimate that 10% of septic tanks are connected to soak pits, although the spatial pattern of buildings with soakaways is unknown.	Evaluate the effect of changing the % of septic tanks connected to a soakaway using different spatial patterns.	Soak pits are used where there is no storm drainage in the street or where the drain is too far away from the building to connect to. The sub catchment area to which the prototype has been applied is built-up with a well-developed drain network and little space for soak pits. Therefore, the number of soak pits in the sub-catchment area is expected to be very low and therefore this assumption will hold. In other parts of the city where	Low	The current model considered all septic tank in the prototype area are connected to the drain but there is evidence 10% septic tank connected to the soak pit. However, without fieldwork, we don't know what the criteria are for such buildings. The sensitivity analysis has been done by considering the following scenarios - <ul style="list-style-type: none"> The model was run without faecal flow from 10% of the larger plots (by sorting the buildings according to their aerial extent, the top 10% of the largest buildings are excluded). 	2- Model run with 10% larger and 10% distant Each includes following steps - <ul style="list-style-type: none"> Selection of buildings Network building Faecal mass flow calculation

			soak pits are used the impact on the output will be greater as the liquid portion of waste will go to the soak pit and stored solids are more likely to be emptied and taken away. Solids that are emptied may not enter the drain and therefore the current assumption would lead to an over-estimate on faecal flows in these areas. Water Aid's estimate of 10% of plots with soak pits may be inaccurate and would need to be checked in the fieldwork validation phase alongside identifying predictors of plots with soakaways.		<ul style="list-style-type: none"> The model was run without faecal flow from 10% of distant plots (by sorting the buildings based on their distance from the nearest drain, the top 10% of the farthest buildings are excluded). 	Approx... done
4. Septic tanks connected to drains are not emptied	26% of households emptied their septic tank once in ten years on an average((Bari, 2017)	Evaluate the effect of changing the % of septic tanks that are emptied using different spatial patterns (uniform, random, spatially-targeted using proxies such as targeting building types more likely to have a maintenance contract e.g. wealthier household and some institutions and businesses)	Current evidence (Bari, 2017) suggests that septic tank emptying is neither frequent nor common and therefore when septic tanks have reached their design storage capacity their solids removal performance will be reduced and solids release to the storm drain will increase. It is known that there is a desludging tanker in the city and a sludge disposal site (Bari et al., 2018). These are indications that a proportion, albeit currently expected to be a small one, of septic tanks are desludged. Establishing the scale of tank emptying and if there are any spatial predictors of likelihood of emptying would be fieldwork tasks.	Low	<p>There is evidence that the city has an informal faecal treatment ground and a desludging vehicle that has been used for septic tank emptying, but there is also evidence that the number of septic tank emptying has been insufficient. According to existing literature, less than 3% of septic tanks are emptied each year, however the exact location or criteria for which buildings are those are unknown. It's possible it is the government institute or hospitals. The fieldwork, on the other hand, will help in the search. Therefore, the sensitivity analysis can be done the following scenarios</p> <ul style="list-style-type: none"> 3% randomly selected building emptied. 10% randomly selected building emptied. <p>These two scenarios hopefully will cover range of building emptied on a yearly basis.</p>	<p>2 – Model run with 1% & 10%.</p> <p>Each includes following steps -</p> <p>Selection of buildings</p> <ul style="list-style-type: none"> Network building Faecal mass flow calculation <p>approx... 1 day</p>
5. Septic tank design has no impact on sludge production rates	In practice, the design, size and management of septic tanks influences their ability to retain and digest sludge. For practical reasons, differences in septic tank performance are not considered in the prototype. There is very low levels of knowledge of the design, operation and performance of septic tanks in such environments and it is currently assumed that septic tanks are very poorly designed and operated.	Not currently included in sensitivity analysis plans but will review after field work.	It is currently assumed that septic tanks so poorly designed and operated that design factors are relatively unimportant. It is assumed that solids removal performance is very poor. This assumption will be challenged after the field work.	Very low	At this time, no sensitivity testing will be done, however, this will be an important criteria for fieldwork. This is particularly in locations where sludge is scraped from drains.	
6. All of the sludge entering the drains from households is transported to the catchment outlet	This is a pragmatic working assumption within the prototype and is expected to change when the prototype is calibrated following fieldwork.	Evaluate the effect of changing the fraction of faecal sludge entering the drain that actually makes it to the sub-catchment outlet using spatially-targeted risk factors	This assumption needs to be challenged and revised in a calibrated model as there is significant reason to believe that there are important exports of sludge from the drain network through drain scraping and potentially unplanned losses through flooding and sediment redistribution.	Moderate	<p>Scraping normally happens in those areas where the faecal solids accumulate. Finding out those places requires field work. However, some proxies can be used in the sensitivity analysis, such as locations with a low slope and a larger ratio of faecal mass flow to drain width.</p> <p>Five places would be selected from the prototype area, two points from each mini-sub catchment (in the</p>	<p>2 – Model run and each one needed to be built separately.</p> <p>Each includes following steps -</p> <ul style="list-style-type: none"> Finding location points

		for accumulation and desludging).	This requires further consideration as part of the fieldwork survey.		western block). At those locations how much faecal scraped off, this is not known so, for the sensitivity range of fraction needed to be consider. Therefore, the following scenario will be tested. <ul style="list-style-type: none"> • 5% of the faecal mass scraped • 25% of the faecal mass scraped • 50% of the faecal mass scraped and • 100% of the faecal mass scraped 	<ul style="list-style-type: none"> • Finding the septic tanks with equivalent volume of faecal mass near to the scraping points • Network building • Faecal mass flow calculation
7. Faecal matter is produced at all buildings irrespective of their types, e.g., residential, commercial or part residential part commercial buildings	For the purposes of the prototype, people have been arbitrarily assigned to all buildings on the basis of their estimated volume, irrespective of building type. To assign population to buildings accurately, it is needed to know each building's information, for example: which building is occupied, or which one is partly use for commercial uses. By using open source data, it is beyond the scope at this moment to know about the land use at building level. Therefore, it is assumed that the uses of non-household toilets are equally important to include when evaluating faecal production in low-income countries as the large number of people who go into urban areas on a regular basis would use those toilets as public toilets are rare.	To do the sensitivity analysis there is a need to identify the buildings which are used for the number of users and duration of use (which should give a better estimate of likely faecal production). There is a way to assess this by taking road-side buildings as commercial. Also, City Corporation may have the data of the uses of the buildings which can be integrated into the model.	If the mixed commercial buildings (office block, shops but warehouse is rare) are more, there is a chance of over estimation of faecal production	Moderate	<p>To do the sensitivity analysis there is a need to identify the buildings which are used for commercial purposes, the number of users and duration of use (which should give a better estimate of likely faecal production). There is a way to assess this by taking road-side buildings as commercial, particularly as partly commercial. Also, City Corporation may have the data of the uses of the buildings which can be integrated into the model.</p> <p>To analyse the spatial pattern and faecal production sensitivity, roadside buildings may be selected and designated as commercial buildings for the initial sensitivity test, and the proportion of faecal output can be increase / decrease in different fractions on those places in the model.</p>	<p>Approx. 1 -week</p> <p>2 scenarios will be run.</p> <p>Each includes following steps -</p> <ul style="list-style-type: none"> • Finding and separating roadside buildings • Network building • Faecal mass flow calculation <p>Approx. 1 -week</p>
8. Faecal matter produced 250 g for each person per day	From the literature an average of 250 g per person per day faecal matter production is widely quoted (Rose et al., 2015). Assumed to reflect the average. In reality, there is likely to be significant variability around this mean in the amount of faecal production which vary between family members and between families because of food habit. In a building there are around 8 to 10	This influence may be tested by taking different average amount but that will not affect the spatial structure in the current data but the magnitude.	Over or under estimation both can happen	Low	This influence may be tested by taking different average amount of faecal production but that will not affect the spatial structure in the current data but the magnitude. Therefore, the sensitivity will not be conducted.	

	families and the faecal production will vary between the individuals. As here we are estimating faecal volume at building level the individual variability may be incorporated within the average we took. Therefore, there is a limited possibility of a significant affect in the faecal production estimation.					
9. Building heights retrieved from elevation data are an accurate basis for attributing population to buildings	The current method of assigning people to buildings is dependent on building volume, which is calculated based on the height and area of the building (Zeng et al., 2014). The volumetric and area metric methods are used to assign people to buildings. Previous studies have found that the volumetric technique is better for attributing people in cities than the area metric method, which is better for rural regions (Greger, 2015).	Uncertainties associated with building height can be reduced by high resolution images (e.g., LiDAR data) or having information on number of floors. To quantify the affect or trying to do the sensitivity analysis will be challenging because it appears that the height reduction is non-linear though there is a pattern. There is a number of factors including mix pixel affect, size and position of the building, and height of the surrounding buildings (Fisher, 1997). Therefore, doing simple reduction or increase in height linearly will not allow assess the sensitivity analysis but random increase or decrease may show spatial pattern of sensitivity.	If the building heights are underestimated in some areas the faecal production will be under estimated and vice versa.	Moderate	To quantify the affect or trying to do the sensitivity analysis will be challenging because it appears that the height reduction is non-linear though there is a pattern. There is a number of factors including mix pixel affect, size and position of the building, and height of the surrounding buildings (Fisher, 1997). However, Increasing the height by 1 and 2 metres, respectively, can be reviewed to assess the spatial pattern of sensitivity.	2 – Model run and each one needed to be built separately. Each includes following steps - <ul style="list-style-type: none"> • Building height calculation • Building volume calculation • Population attributing • Faecal production calculation • Network building • Faecal mass flow calculation Approx... 2 -weeks
10. Area of the buildings from Open street map is accurate representation of area of each building	Area of the buildings came as an attribute of building data	There are some built in uncertainties within it like the digitisation errors.	If the areas are under / over estimated it will effect the spatial pattern of faecal distribution.	Low	This parameter has a sensitivity as well, although determining the change in the spatial pattern may be difficult. However, doing a sensitivity analysis with a 10% increase or reduction will reveal the spatial pattern of sensitivity.	2 – Model run and each one needed to be built separately. Each includes following steps – <ul style="list-style-type: none"> • Area calculation • Building height calculation • Building volume calculation

						<ul style="list-style-type: none"> • Population attributing • Faecal production calculation • Network building • Faecal mass flow calculation <p>Approx... 2 -weeks</p>
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References:

- Bari, N. (2017). Study on Existing Faecal Sludge Management Situation in Rajshahi Rajshahi City. *Proceedings of the WasteSafe 2017 – 5th International Conference on Solid Waste Management in South Asian Countries 25-27 February 2017, Khulna, Bangladesh STUDY, March.*
- Bari, N., Bushra, A., & Zaman, J. (2018). Management of faecal sludge by rajshahi city corporation. *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development, July*, 1–11. http://www.iccesd.com/proc_2018/Papers/r_p4803.pdf
- Fisher, P. (1997). The pixel: A snare and a delusion. *International Journal of Remote Sensing*, 18(3), 679–685. <https://doi.org/10.1080/014311697219015>
- Greger, K. (2015). Spatio-temporal building population estimation for highly urbanized areas using GIS. *Transactions in GIS*, 19(1), 129–150. <https://doi.org/10.1111/tgis.12086>
- Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Critical Reviews in Environmental Science and Technology*, 45(17), 1827–1879. <https://doi.org/10.1080/10643389.2014.1000761>
- WaterAid. (2018). *SFD Lite Report of Rajshahi City Corporation Bangladesh.*
- Zeng, C., Wang, J., Zhan, W., Shi, P., & Gambles, A. (2014). An elevation difference model for building height extraction from stereo-image-derived DSMs. *International Journal of Remote Sensing*, 35. <https://doi.org/10.1080/01431161.2014.975375>

Appendix C Sensitivity Analysis (Chapter 3)

The sensitivity of the five selected assumptions was analysed to determine their influence on the model outputs (Table 3.1). The sensitivity analysis used alternative assumptions, as detailed in Table B- 2, to evaluate the model's outcomes. The results of this analysis are described and discussed in Chapter 3, along with an example of the outcomes. The remainder of the outcomes is presented here (**Figure C- 1 to Figure C- 4**).

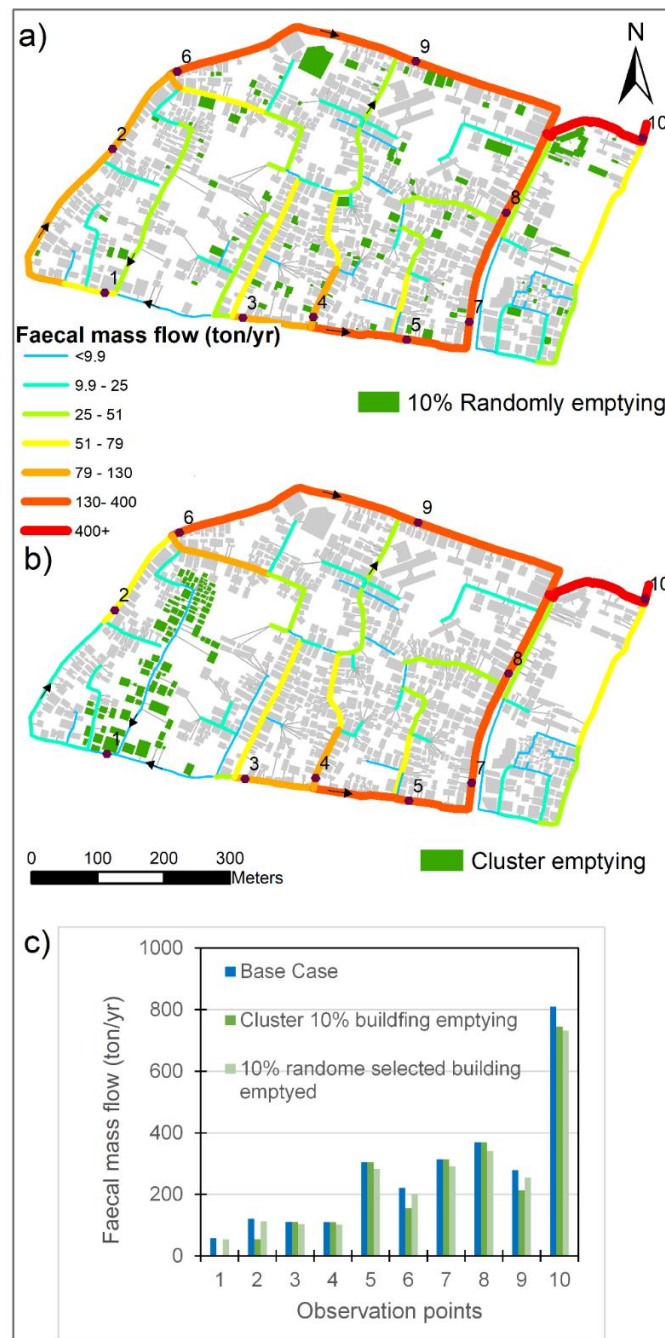


Figure C- 1: Sensitivity analysis and the spatial representation of influencing factor. Here the analysis shown number 2(A) and 2(B) in Table 3.1. Septic tanks connected to drains are not emptied considering the alternative assumption with two variants. The maps represented the simulated spatial location of the buildings while the graph showed the spatial variability in 10 selected locations, capping at 400+ to best detail the range seen in most areas. The bar graph, however, extends to 800+ to accurately represent the unique conditions at the outlet.

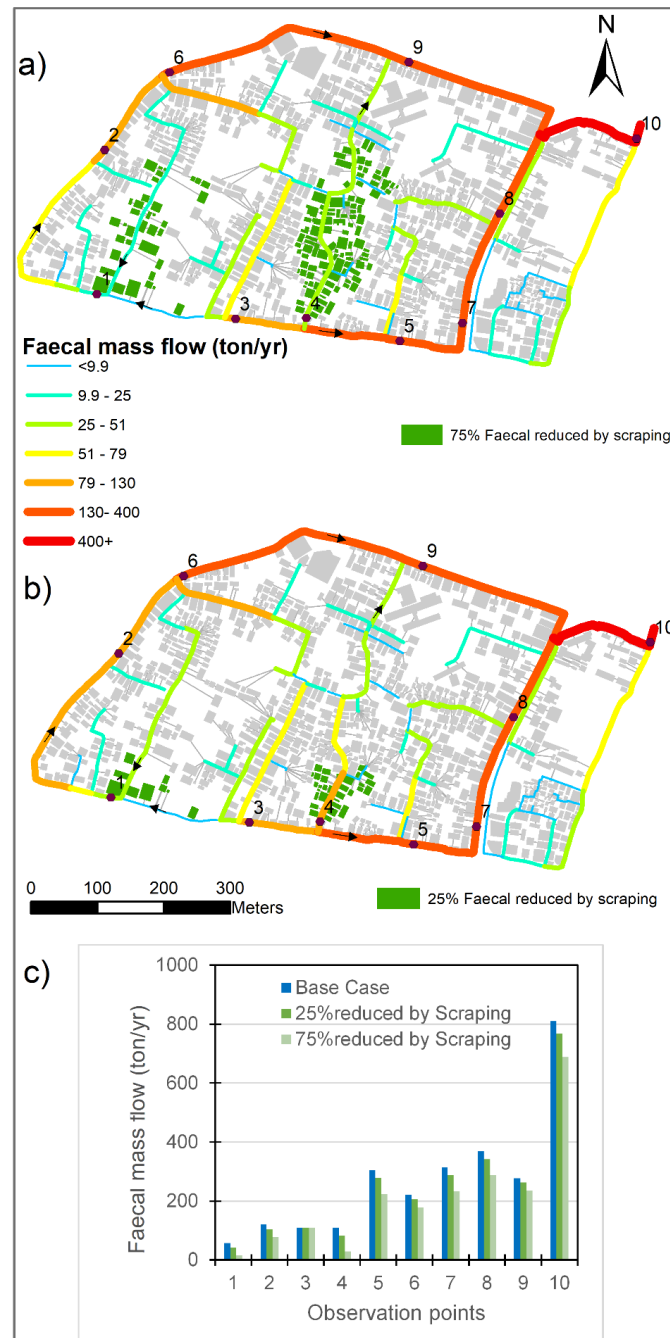


Figure C- 2: Sensitivity analysis and the spatial representation of influencing factor. Here the analysis shown number 3(A) and 3(B) in Table 3.1. Some drain scrapping considering the alternative assumption with two variants. The maps represented the simulated spatial location of the buildings while the graph showed the spatial variability in 10 selected locations, capping at 400+ to best detail the range seen in most areas. The bar graph, however, extends to 800+ to accurately represent the unique conditions at the outlet.

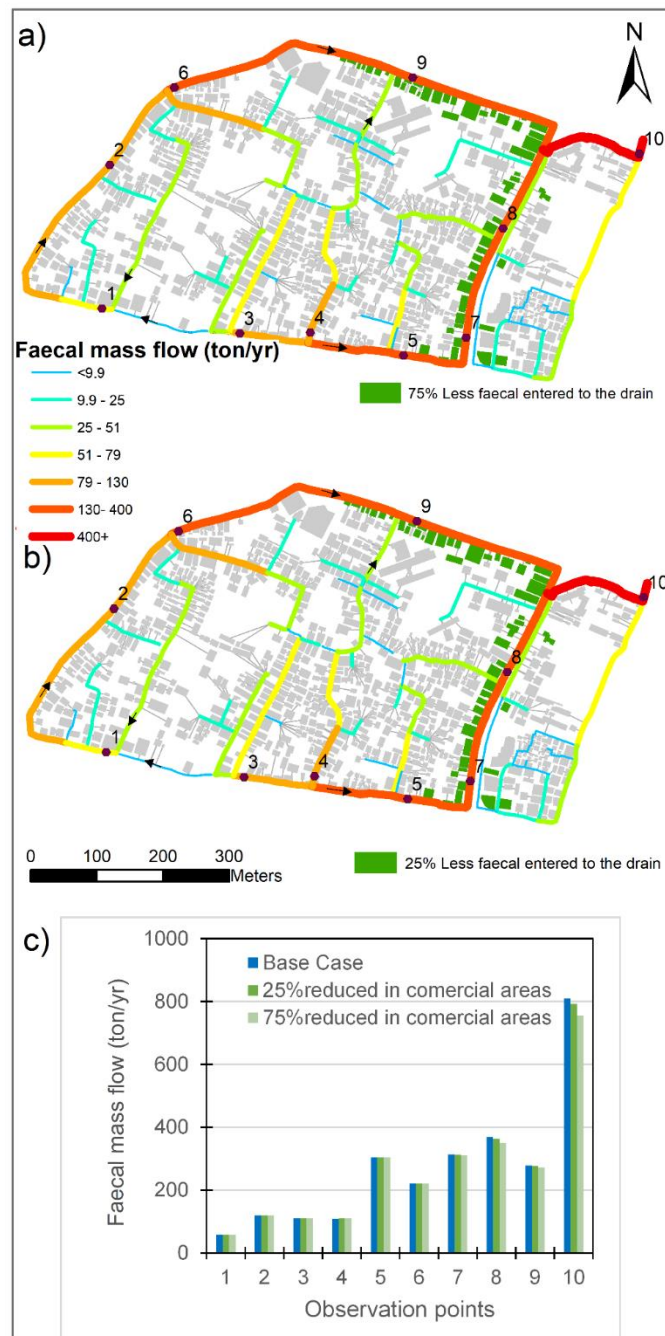


Figure C- 3: Sensitivity analysis and the spatial representation of influencing factor. Here the analysis shown number 4(a) and 4(b) in Table 3.1 considering the alternative assumption linked to commercial buildings with two variants. The maps represented the simulated spatial location of the buildings while the graph showed the spatial variability in 10 selected locations, capping at 400+ to best detail the range seen in most areas. The bar graph, however, extends to 800+ to accurately represent the unique conditions at the outlet.

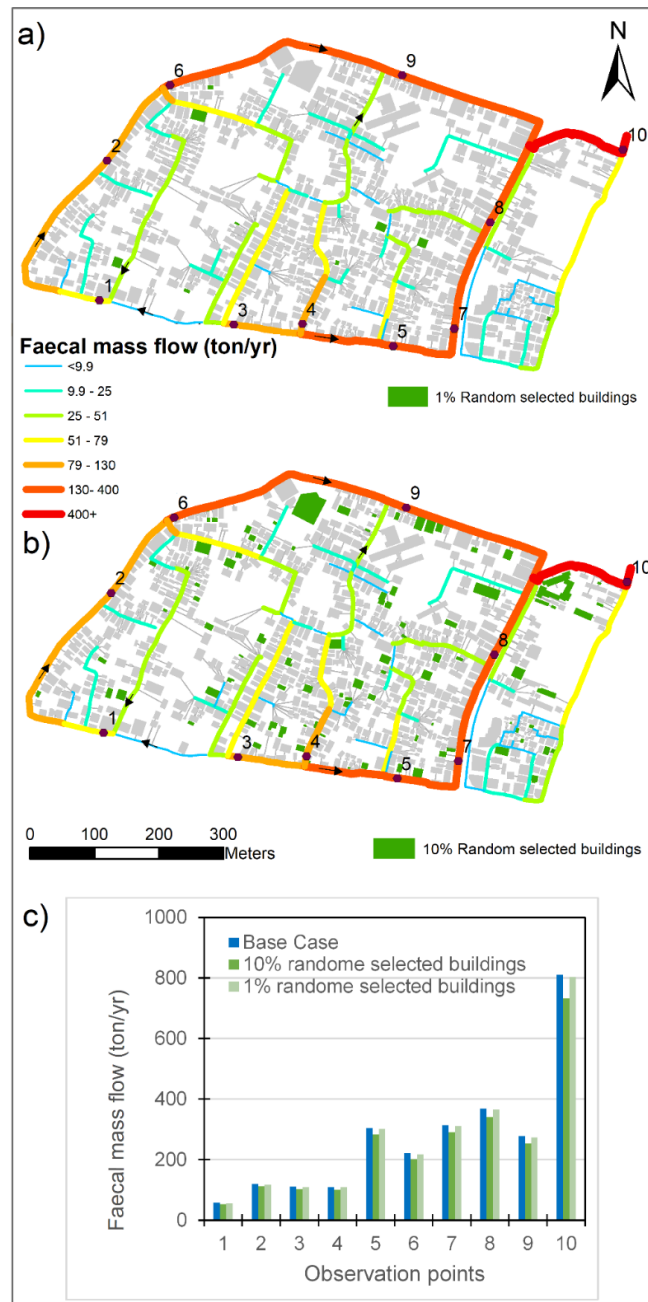


Figure C- 4: Sensitivity analysis and the spatial representation of influencing factor. Here the analysis shown number 5(a) and 5(b) in Table 3.1 considering the alternative assumption with two variants where there is no toilet in certain fraction of buildings. The maps represented the simulated spatial location of the buildings while the graph showed the spatial variability in 10 selected locations, capping at 400+ to best detail the range seen in most areas. The bar graph, however, extends to 800+ to accurately represent the unique conditions at the outlet. 20240617