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An analysis of factors that influence the spatial pattern of faecal matter flow in unsewered cities

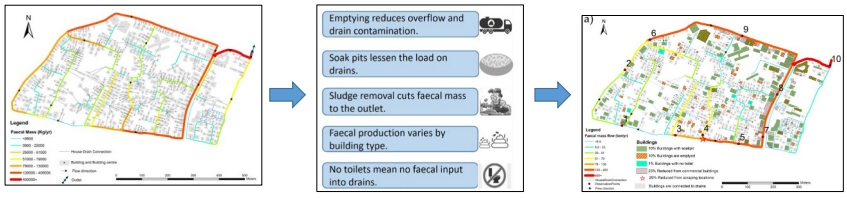
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HIGHLIGHTS

- 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.

GRAPHICAL ABSTRACT



Base case model with assumption that all faecal matter ends up to the drain.

Addressing uncertainty and considering influencing factors

Modified model ~ 50% reduction in faecal flow after considering the influencing factors.

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ABSTRACT

The management of sanitation systems in unsewered cities in low and middle income 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 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.

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1. Introduction

In many economically low and middle income countries, cities with populations exceeding one million face significant challenges in sanitation management (Ezechiel and Baptiste Safari, 2020). Typically, sanitation systems are individually owned, relying on septic tanks and pits (Strande et al., 2018), making comprehensive city-wide management difficult to coordinate and predict. The lack of adequate sewer infrastructure in many cities means wastewater is often managed through local drainage systems, which were not designed for this purpose (Mills et al., 2018; Peal et al., 2020). This, combined with irregular emptying of septic tanks (Bari, 2017; Mehta et al., 2019), leads to the overflow of faecal matter into drains, creating public health risks, especially during extreme weather events like floods and heavy rainfall (Foster et al., 2021; Robb et al., 2017; Tabassum, 2020).

Developing effective sanitation management systems requires time, resources, expertise, and reliable data which many cities lack (Blackett et al., 2014; Kone, 2010). In Dhaka, nearly one-third of urban residents lack access to safely managed sanitation services (Alam et al., 2020; Amin et al., 2020), and the situation is even more dire in regional cities, often referred to as secondary cities, where almost all sanitation is managed at a personal level (Bari, 2017; Mehta et al., 2019). These challenges highlight the urgent need for improved sanitation management, especially in densely populated areas, where pathogen flows from on-site sanitation systems pose significant health risks. Recent studies have emphasized the importance of data-driven models in assessing public health impacts and informing sanitation decisions (Foster et al., 2021).

Understanding faecal waste flows has historically been limited by a lack of spatial data, particularly in urban environments. A study in Kumasi, Ghana (Whittington et al., 1993) marked one of the earliest efforts to understand faecal waste flows by relying heavily on household surveys to gather data on waste generation and disposal practices. While this approach provided valuable insights at the household level, it failed to capture the complex spatial dynamics of faecal flow across urban areas. More recent studies have faced similar limitations (CWAS, 2020; Hawkins and Muxímpua, 2015), revealing the ongoing challenge of achieving extensive data coverage necessary for understanding faecal movement within diverse cityscapes. Tools like the excreta flow diagram (SFD) offer citywide overviews of faecal sludge flows (Peal et al., 2020); however, they often overlook the spatial variability within cities, which is crucial for identifying local differences in sanitation practices and infrastructure (Leidig et al., 2016). To address this gap, a methodology developed by (Sultana et al., 2023), which uses open-source data to spatially represent sanitation systems. This approach maps faecal matter sources and movement pathways from buildings to drainage outlets, offering a novel way to understand the spatial dynamics of faecal flow. However, the methodology relies on several assumptions, such as faecal matter from all buildings entering local drains, which may not fully reflect real-world conditions. Individual buildings may employ different practices, such as using soak pits or emptying septic tanks at varying intervals, leading to spatial variability that is often unaccounted for in traditional models.

These challenges underscore the need for more localised, data-driven approaches that capture faecal matter movement at a finer spatial scale, enabling targeted interventions and more effective sanitation management in resource-constrained environments.

This study focuses on Rajshahi, a secondary city in northwest Bangladesh, to evaluate how various assumptions and uncertainties affect the spatial representation of faecal flow patterns. The primary objectives are to assess and identify the most important influencing factors, analyse the sensitivity of each factor, and evaluate the combined influence of these factors by comparing the model outcomes with the base case scenario. By identifying high-risk areas based on spatial faecal concentration and understanding the drivers of this variability, the study offers new insights into the spatial dynamics of faecal mass in unsewered cities.

This approach may support global efforts to achieve the Sustainable Development Goals, particularly SDG 6.2 (ensuring access to adequate and equitable sanitation) and SDG 6.3 (improving water quality by reducing pollution). By providing a method to quantify and visualize faecal mass flows, the study enhances the ability of municipal stakeholders to monitor sanitation risks and manage faecal pollution in underserved urban areas. Such spatial visibility is essential for guiding evidence-based, inclusive sanitation planning. Also, these insights can help local authorities prioritise interventions and allocate limited resources more effectively, directing efforts to areas with the greatest need.

2. Data and method

2.1. Data

The model by Sultana et al. (2023) integrates diverse data sources to estimate population distribution, faecal production per building, and the connectivity from buildings to drains, subsequently visualizing this data through a faecal mass flow map. The study employs GIS techniques for the analysis and model development (Fig. 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 subsequently calculate faecal mass based on a standardised per capita production rate of 250 g/d (Rose et al., 2015), while drainage maps are used to link buildings to the nearest drain to infer flow directions (Li et al., 2020). Where possible, the data were triangulated with field observations and local knowledge, which provided further confirmation of the patterns observed. Although these spatial datasets (e.g., OpenStreetMap, LandScan, and ALOS PALSAR DEM) have rarely been applied in the sanitation field, they are widely used in the spatial and environmental sectors (Coetzee et al., 2020; Rana and Adhikary, 2020; Vu et al., 2021). This modelling exercise was the first to demonstrate the spatial pattern of faecal flow in an unsewered urban catchment showing how integrating multiple spatial data sources can generate insightful analyses of sanitation systems.

To further improve the model's accuracy and assess its uncertainty, a qualitative analysis was conducted to categorise the assumptions into classes based on their assessed influence in faecal production and movement. A detailed list of these assumptions and their qualitative evaluation can be found in Table S1 in the supplementary information and the summarised version in Fig. 3. Also, a sensitivity analysis was conducted to quantify the influence of key assumptions (Table 1). The empirical data on these key assumptions were gathered from the literature and anecdotal evidence in conjunction with relevant secondary data sources (Sultana et al., 2023). To ensure the validity and reliability of the empirical data, we cross-checked the information from multiple sources, including published studies, reports from local authorities, and expert consultations.

2.2. Data analysis

A protocol has been designed to assess uncertainty of the assumptions and the sensitivity of the key assumptions by contrasting the outcomes against the base-case model (Fig. 2). To measure the impact of the key assumptions, ten observation points have been selected across the model area, including one close to the outlet of the catchment (Fig. 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.

2.3. Method

2.3.1. Identifying key assumptions

In the model (Fig. 1), ten assumptions were made due to the lack of field data on local sanitation practices and infrastructure (Sultana et al., 2023). A qualitative analysis enabled us to categorise the assumptions into classes based on their assessed influence: low, moderate, or high (Table S1 and Fig. 3). Assumptions with a high level of influence were those expected to generate substantial spatial variability in faecal movement, either by changing how faecal matter interacts with the drainage network or by creating clusters of varying faecal production across different zones. Ultimately, five assumptions were identified as having a high potential to influence the spatial character of faecal production and movement. These influential assumptions were: (1) all buildings have toilets and septic tanks; (3) all septic tanks are connected to drains, not soak pits; (4) septic tanks connected to drains are not emptied; (6) all sludge entering drains reaches the catchment outlet; and (7) all buildings produce faecal matter, regardless of their type. These assumptions were retained for further sensitivity analysis to assess their impact on the spatial structure of faecal movement within the urban environment (Table 1).

During this evaluation process, assumptions judged to have minimal impact on the spatial distribution of faecal flow were excluded from subsequent analysis. For instance, the assumption that septic tanks are always located at the centre of each plot (Assumption 2) was deemed unlikely to affect the faecal movement pattern meaningfully. Due to the typically small plot sizes and the gravity-driven nature of the drainage system (Li et al., 2020), any variation in septic tank positioning was expected to lead to minimal deviation in faecal flow pathways. Similarly, Assumption 5, concerning septic tank design and size, was also not included in the sensitivity analysis due to the lack of detailed data and the absence of on-site surveys to validate design variability. However, the sensitivity analysis of soak pits (Assumption 3) and emptying (Assumption 4) provides insights into how septic tank design and size might influence faecal movement patterns. Furthermore, Assumptions (9 and 10) regarding certain uniform characteristics—such as building height or open-source building area data—were considered unlikely to alter spatial dynamics in a significant way, as any errors or inconsistencies were assumed to be evenly distributed across the study area.

By focusing on assumptions considered to have a substantive effect on spatial faecal dynamics, this methodology ensured that the subsequent sensitivity analysis was both targeted and capable of highlighting key uncertainties influencing model outcomes.

2.3.2. Assessing the sensitivity of the key assumptions

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. The model employs a fixed

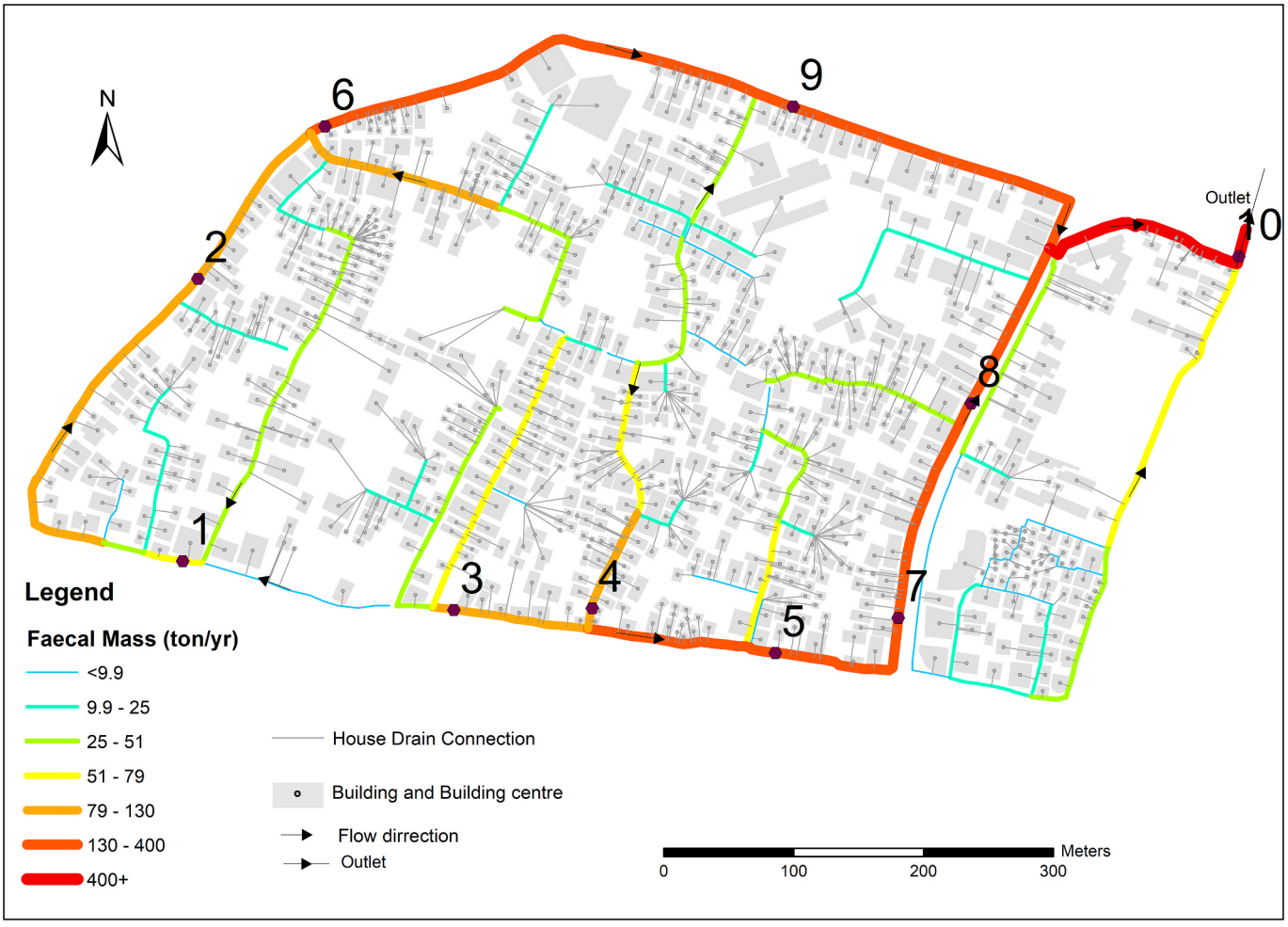


Fig. 1. The spatial pattern of faecal flow in an unsewered urban catchment Kazihata, Rajshahi (adopted from Sultana et al., 2023). Here we can see ten observation points that were used in the sensitivity analysis.

Table 1
Five assumptions were selected (1, 3, 4, 6, 7) to assess their sensitivity. To do the sensitivity, plausible alternative assumptions were chosen (column 2). Two scenarios were considered, variants (A) most plausible, and variant (B) less plausible, have been produced in column 3 to assess and spatially represent alternative assumptions.

Selected five key assumptions	Alternative assumptions and its rational	Variants	
		Most plausible variants (A)	Less plausible variants (B)
All buildings have toilet and septic tank (Assumption 1)	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 Fig. S-1 in supplementary information.	10 % randomly selected buildings which do not have toilets Fig. S-1 in supplementary information.
All septic tanks are connected to the drains rather than a soak pit (Assumption 3)	10 % buildings uses soak pits. 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 (Fig. 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 (Fig. 4).
Septic tanks connected to drains are not emptied (Assumption 4)	10 % buildings emptied their septic tanks. It is probable that up to 10 % of septic tanks in the 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.	10 % of randomly selected buildings were chosen for analysis. These buildings represent a diverse range of areas in the city, and their septic tanks are assumed to be emptied regularly see in Fig. S-2 in supplementary information.	A spatial cluster equivalent to 10 % of buildings was created 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 Fig. S-2.
All of the sludge entering the drains from households is transported to the catchment outlet (Assumption 6)	Some sludge scraped off from the drain therefore does not reach to the 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 the sensitivity analysis.	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 amount produced, the map showed in Fig. S-3 in supplementary information.	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 transport of all the waste material to the catchment outlet Fig. S-3.
All buildings produce faecal matter irrespective of their types (Assumption 7)	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 Fig. S-5 in supplementary information.	In addition, a higher reduction of 75 % in faecal matter production from buildings designated as commercial Fig. S-4 in supplementary information.

value approach, rather than testing a range of values for factors like the percentage of septic tanks emptied or soak pits used. This approach was chosen because the primary aim of the model is to explore spatial variation, rather than to assess the range of varying percentages.

A single value of 10 % was used for both septic tank emptying and soak pit use (assumptions 3 & 4), based on data from existing literature and expert judgement of plausible value for the city (as detailed in Supplementary Information, Table S1). This method allows for a focused examination of how these fixed assumptions influence the spatial distribution of faecal matter, rather than investigating the broader variability in these parameters.

To see the spatial impact of the alternative assumption of soak pit use and to display this on the map there were two scenarios considered for each assumption: one focusing on larger buildings uses soak pit and other on the distant buildings uses soak pit. Larger buildings are defined as being those buildings with an aerial footprint in the top decile of buildings of the study area, i.e. of >200 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.

Also, another alternative assumption considered that 10 % of buildings emptied the septic tanks instead discharging all faecal to the drains. This spatial variation was assessed by employing two spatial

variants e.g., randomly selected 10 % buildings and 10 % buildings in a single street (i.e., clustering as a classification technique where buildings are selected according to location on a street (Gil et al., 2012)). For other assumptions, different alternate situations were considered as detailed in Table 1.

2.3.3. Assessing the combined influence

A set of alternative assumptions were developed to reflect plausible spatial variations, incorporating both the most plausible and less plausible combinations of key assumptions (Table 1). The analysis considered 252 possible combinations of influencing factors 10C5 = 10!/5! (10–5)! However, a deterministic sensitivity analysis approach was chosen for this study to balance practical constraints and research objectives. This approach focused on key assumptions that were deemed most influential, allowing for a targeted exploration of their combined effects on spatial faecal flow variability.

The deterministic method was selected over probabilistic approaches, such as Monte Carlo simulations, due to the lack of comprehensive empirical data and the need to minimize computational complexity. While this method does not account for the full range of variability and uncertainty, it provides a simplified yet actionable framework to examine spatial dynamics in unsewered urban environments (Borgonovo, 2008; Saltelli et al., 2020).

The most plausible variants were combined and compared with the base case model and the less plausible variants were also combined and analysed in the same way (Fig. 5).The combined impact of five factors were assessed at 10 locations within the model area and compared as discussed in section 2.2.2.

3. Results

3.1. Selection of key assumptions

The qualitative evaluation identified which of the ten initial assumptions would most significantly influence the spatial variability of faecal flow within the urban area (Fig. 3). Ultimately, five assumptions were retained for sensitivity analysis due to their perceived impact on the spatial distribution of faecal matter, while the other five were excluded based on their limited influence or uniform effect.

Assumption 1 underscored the critical role of sanitation infrastructure in shaping faecal distribution, particularly in areas like slums or regions with pit latrines, where a lack of infrastructure could lead to noticeable spatial clusters of faecal accumulation. Similarly, Assumption 7 addressed the variability in faecal production between residential and commercial buildings, where differences in usage patterns could spatially affect the faecal load. Assumption 3 (connection of septic tanks to soak pits) and Assumption 4 (septic tank emptying) both influenced how faecal matter entered the drainage system, contributing to spatial variability in the flow. Finally, Assumption 6 highlighted the drainage system's role in determining where faecal matter accumulates or is deposited, further affecting spatial variability.

The remaining five assumptions were excluded due to their minimal impact on spatial faecal dynamics or their uniform influence across the study area. For example, Assumption 2 (septic tanks always located at the centre of each plot) was unlikely to significantly affect spatial flow patterns given small plot sizes and the gravity-driven drainage system. Assumption 5 (septic tank design and size) was excluded, as the

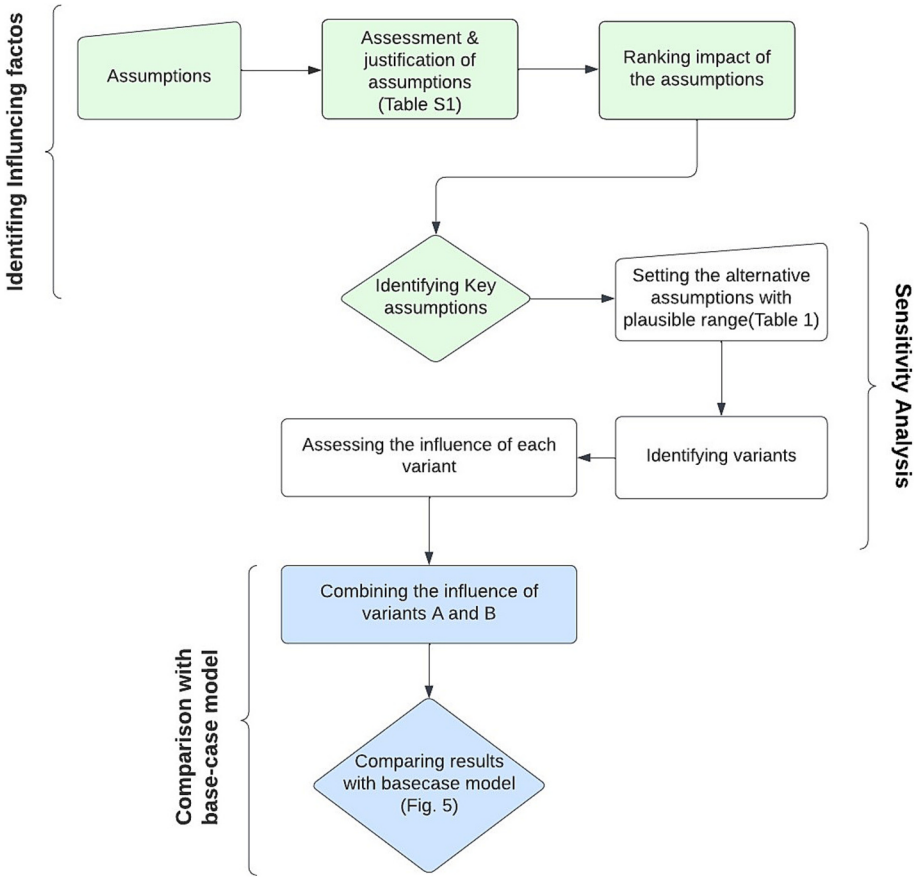


Fig. 2. Flow chart of the methodology. There are three major steps in the analysis separated by the sheds of three colour, i) Identifying influencing factors (Key assumptions) (Fig. 3), ii) Sensitivity analysis by setting up alternative assumptions with variants (Table 1), and finally iii) assessed the combined influence of all factors and comparing the model outcome with base case model Fig. 5. The symbols used are conventionally applied: the parallelogram represents manual input, the rectangle indicates process steps, and the diamond signifies decision points.

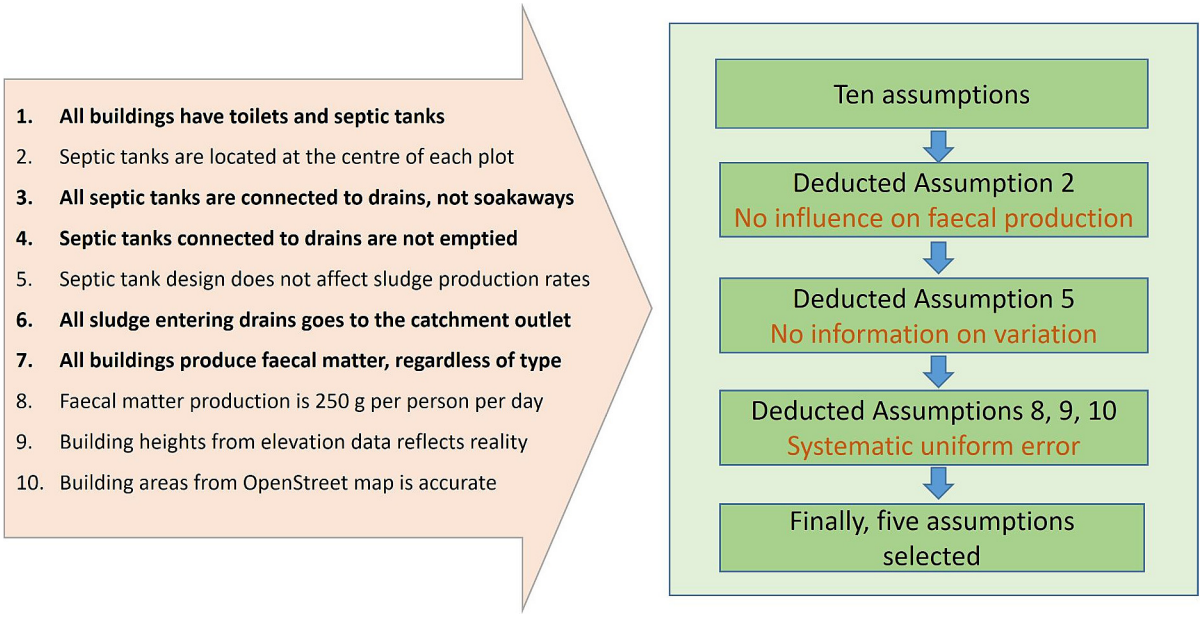


Fig. 3. Analysing assumptions and identifying five of them which are considered most likely to influence the spatial pattern of faecal matter flow. The left-hand side of the figure shows ten assumptions which were used to build the base case model (Sultana et al., 2023). The right-hand side panel shows briefly why some assumptions were excluded from the sensitivity analysis (detailed can be found in supplementary information (Table S1). 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.

available data did not provide enough spatial heterogeneity to make it impactful. Assumption 8 (faecal matter production of 250 g per person per day) was assumed to be largely uniform, with minimal demographic variation affecting the spatial structure. Similarly, Assumptions 9 and 10 (building height and area data) were excluded, as any errors were likely consistent across the city and thus unlikely to influence spatial faecal dynamics (Fig. 3).The selection process emphasized that assumptions related to connectivity and sludge management practices (Assumptions 1, 3, 4, and 7) and movement pathways (Assumption 6) had the greatest influence on faecal movement patterns. In contrast, more uniform parameters (Assumptions 8, 9, and 10) had a lesser effect. These selected assumptions formed the basis for the sensitivity analysis, as detailed in the following section.

3.2. Sensitivity of five selected assumptions

This section examines the model's sensitivity to five selected assumptions. (1) all buildings have toilets and septic tanks; (3) all septic tanks are connected to drains, not soak pits; (4) septic tanks connected to drains are not emptied; (6) all sludge entering drains reaches the catchment outlet; and (7) all buildings produce faecal matter, regardless of their type.

3.2.1. All buildings have toilets and septic tanks (assumption 1)

The model considered two scenarios for the sensitivity analysis: in variant A, excluded 1 % buildings and in variant B, excluded 10 % randomly selected buildings without toilets and septic tank (Table 1). 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 (Fig. S1).

3.2.2. All septic tanks are connected to drains, not soak pits (assumption 3)

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 %) (Fig. 4).

3.2.3. Septic tanks connected to drains are not emptied (assumption 4)

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 (Fig. S2). 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.

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.

3.2.4. All sludge entering drains reaches the catchment outlet (assumption 6)

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 points 1 and 4) and at the two different scraping rates specified reduced faecal mass at the outlet by 5 % and 15 % respectively (Fig. S3).

3.2.5. All buildings produce faecal matter, regardless the type. (Assumption 7)

The model was run with 25 % and 75 % reduced faecal production from commercial buildings. 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 (Fig. S4).

3.3. Combined influence of key assumptions

3.3.1. Most plausible variants combined (As)

The spatial representation of faecal mass flow under the variant As of alternative assumptions (Table 1), which are considered more plausible, are depicted in the map (Fig. 5a).

The characteristics of this scenario include the presence of soak pits in 10 % of larger buildings, septic tanks being emptied in another 10 % of buildings selected as a representative sample, and 1 % of buildings identified as having no toilets based on realistic spatial patterns.

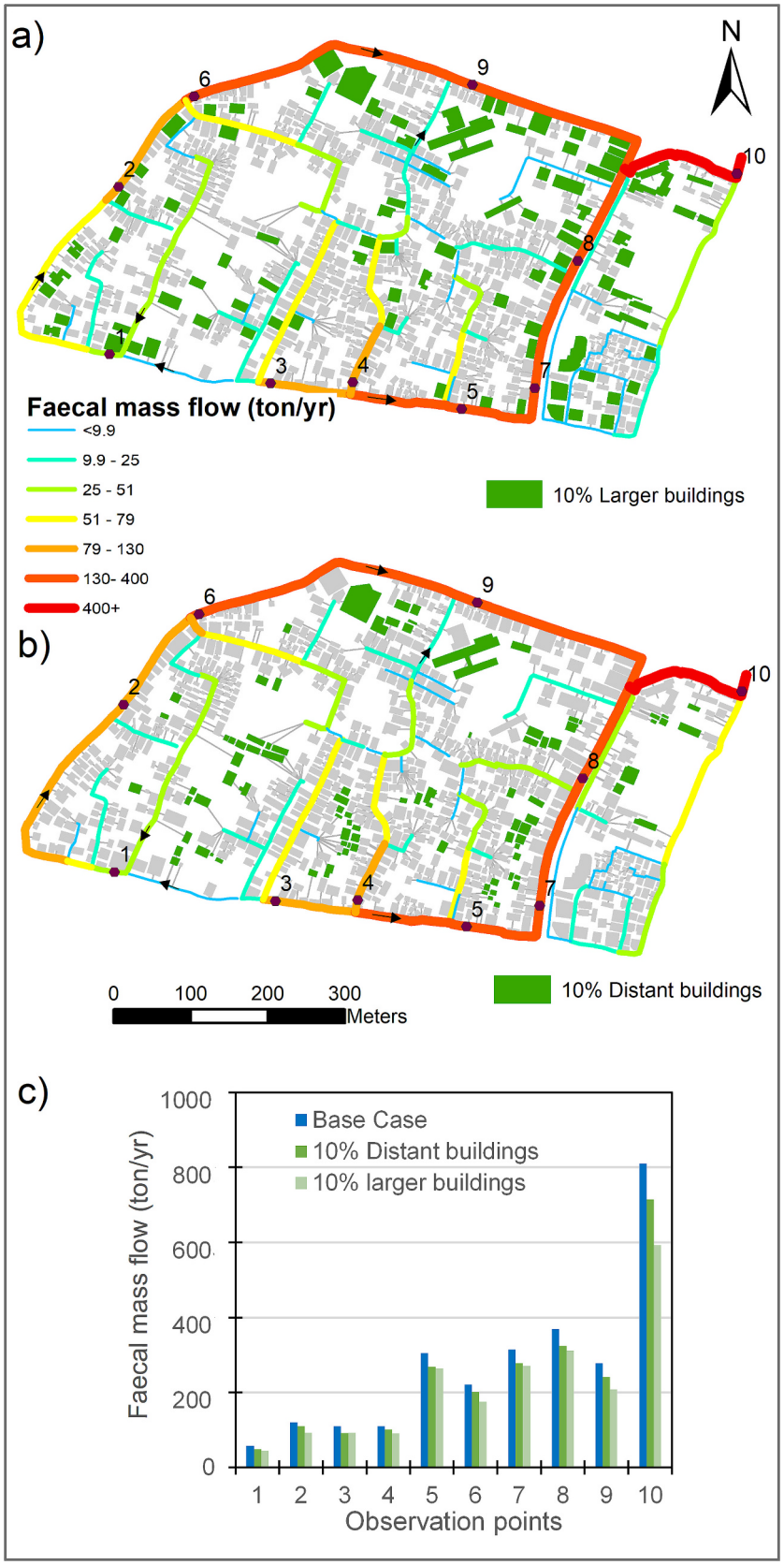


Fig. 4. Sensitivity analysis and the spatial representation of influencing factors (Assumption 3). Here we have shown analysis number 1(A) and 1(B) in Table 1. Some septic tanks are connected to soak pits rather than drains considering the alternative assumption with two variants. The maps represented the simulated spatial location of the buildings.

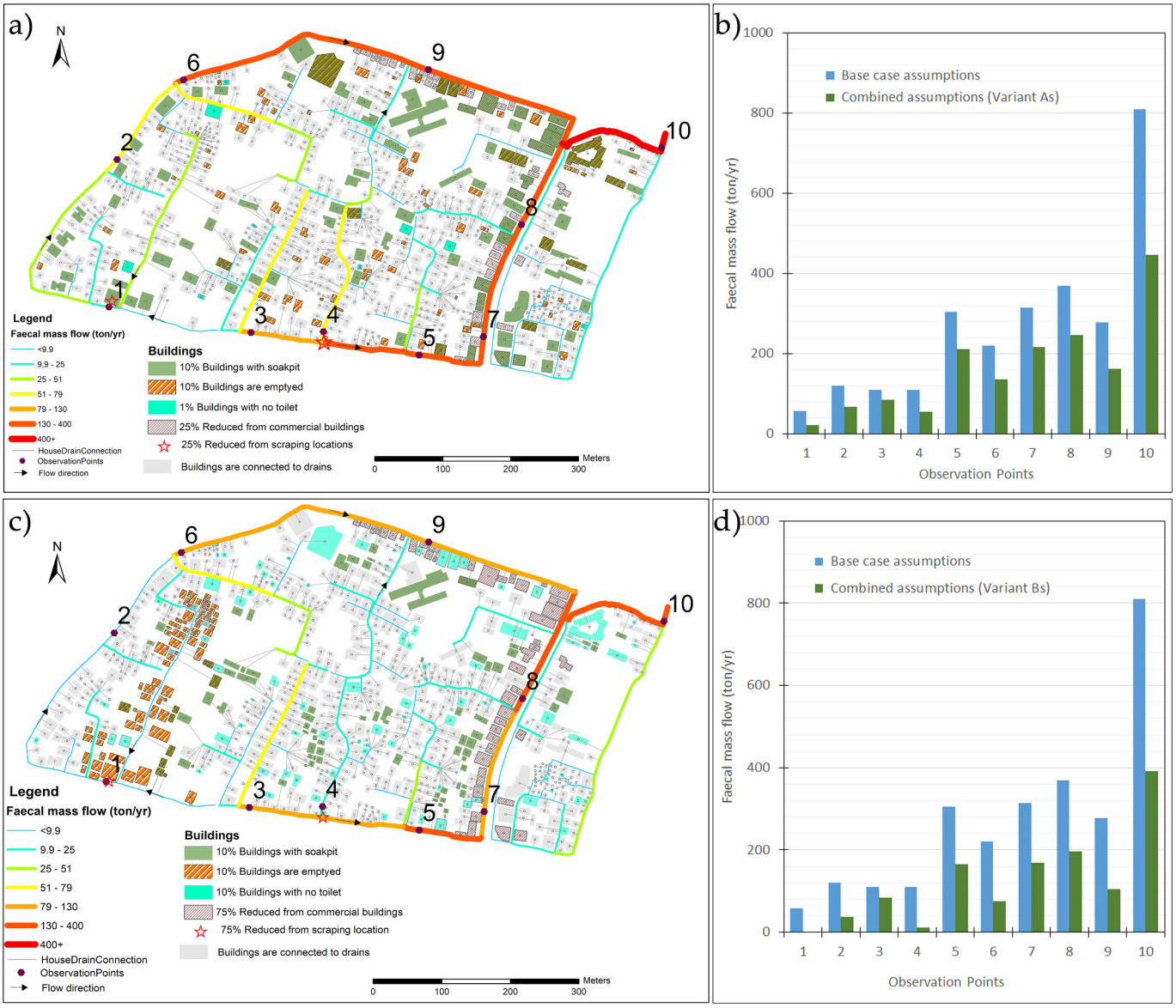


Fig. 5. The maps provide a spatial and quantitative comparison of two sets of variants, As and Bs, in their distribution and faecal mass flow, with reference to a base case model. Variant As is depicted through the simulation of five factors and their associated faecal mass flows at ten observation points. Variant Bs presents a different set of factors and their flow rates at the same locations. The maps indicate the locations of particular buildings and the variations in faecal flow at the observation points. The bar graph illustrates flow levels up to 400+ ton/yr to demonstrate typical circumstances, while 800+ ton/yr represents the exceptional conditions at the outflow.

Additionally, there are reductions in faecal output from commercial buildings and specific locations where sludge scraping occurs, both marked at 25 %.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 (Fig. 5b) 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.

3.3.2. *Less plausible variants combined (Bs)*

Fig. 5 (c) also, 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, it assumes the presence of soak pits in 10 % of distant buildings, the emptying of septic tanks along one entire street selected as a representative sample in another 10 % of buildings, and 10 % of buildings identified as having no toilets based on a broader, less likely pattern. These alternative assumptions have made the faecal flow reduction by 12 %, 8, 15 %, 7 % and 10 % respectively.

The corresponding bar chart (Fig. 5d) 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 a 10. In the bar chart shown in Fig. 5 (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 less plausible variants and the base-case model is 52 %.

4. Discussion

4.1. Assumptions as a basis for identifying influencing factors

Identifying the key influencing factors is important to understand the spatial dynamics of faecal flow in unsewered cities (Peal et al., 2020; Whittington et al., 1993). By using a set of structured assumptions, this study addresses the gap in existing sanitation models, which typically treat cities as homogenous units, by focusing on the spatial variability of faecal movement. The research aimed to provide actionable insights for local authorities to better manage sanitation, particularly by identifying high-risk areas. Five significant factors influencing faecal flow were highlighted, relating to Assumptions 1, 3, 4, 6, and 7 (Table 1): some buildings lack sanitation facilities (1), septic tanks are connected to soak pits instead of drains (3), some septic tanks emptied regularly and not connected to drains (4), not all sludge reaches the catchment outlet (6), and faecal production varies by building type (7). These factors drive significant spatial differences in faecal flow.

While this study did not directly conduct a sensitivity analysis on septic tank design and size (Assumption 5). However, insights from the sensitivity analysis of using soak pits (Assumption 3) and emptying septic tank (Assumption 4) suggest that variations in tank design and size could influence faecal movement patterns (Fig. 4). Septic tank size, for instance, can affect how quickly the tank fills up—larger tanks may hold more faecal matter, requiring less frequent emptying, while smaller tanks may reach capacity faster, potentially leading to the release of faecal matter into the drainage system. Additionally, well-designed septic tanks with integrated soak pits may not release faecal matter into drains, whereas poorly designed or absent soak pits may contribute to higher faecal flow into the drainage network (e.g., Withers et al., 2011).

The study reveals that septic tank size and design vary based on factors such as local construction practices, household size, and environmental conditions. Features like multiple chambers or integrated soak pits can reduce the faecal matter entering the drainage system (Montangero and Belevi, 2007; Tilley et al., 2014), but the currently available information does not support significant variation in sizes or design of septic tanks in Rajshahi (Bari, 2017; HBRI, 2015). Therefore, future research should aim to gather detailed field data to further explore these dynamics.

Previous studies (e.g., Peal et al., 2020) have provided citywide overviews of faecal sludge flows but did not capture the spatial differences within cities that significantly impact faecal management. This research expands on the literature by offering a model that highlights the importance of sanitation infrastructure (Assumptions 1 and 7), connectivity to drainage systems (Assumptions 3 and 4), and sludge management (Assumption 6). By identifying high-risk areas based on faecal concentration and understanding the factors driving spatial variability lays the groundwork for more spatially sensitive sanitation management strategies, ultimately contributing to proactive and data-driven sanitation management in unsewered cities.

4.2. Understanding spatial variability of faecal flow

Spatial variability in faecal flow is shaped by a range of influencing factors, including soak pit usage, septic tank emptying, and differences in building types (e.g., commercial vs. residential) (Fig. 5). However, the spatial distribution of these factors is not well-documented, making it challenging to pinpoint their exact contributions to faecal movement patterns. To address this, we employed sensitivity analysis to explore the spatial representation of these factors and their individual and collective impacts on faecal flow variability.

This approach provides insights into how specific practices, such as soak pit usage in larger buildings or targeted septic tank emptying, can reduce faecal flow (Fig. 4). By analysing these scenarios, we aim to identify high-priority areas for intervention and inform sanitation strategies tailored to the spatial dynamics of unsewered urban environments.

The model evaluated the impact of soak pit usage under two scenarios: 10 % of larger buildings and 10 % of buildings located furthest from the drainage system were assumed to have soak pits (Fig. 4). This analysis explored how spatial variability in soak pit distribution affects faecal flow. Buildings with soak pits, often mandated by institutional or regulatory standards (HBRI, 2015), showed varied impacts based on their proximity to drainage systems. Larger buildings with soak pits, such as institutional facilities or large residential complexes, typically located closer to main roads and drains, tended to reduce faecal flow more significantly due to their higher faecal loads. In contrast, distant buildings with soak pits were generally mixed in size and often smaller. These buildings had a less effect on faecal flow, partly because their reduced faecal loads and limited direct connectivity to drainage networks lessened their contribution to spatial variability. However, the functionality of soak pits is often compromised by poor design, non-compliance with standards, and geological conditions unsuitable for infiltration (Mbae et al., 2024). Additionally, the lack of effective monitoring systems exacerbates these challenges, reducing the overall effectiveness of soak pits in managing faecal flow.

The model tested a 10 % septic tank emptying rate using both cluster and randomised selection methods, allowing for an assessment of targeted versus uniform faecal matter removal strategies (Fig. S2). Results showed that cluster selection, which targeted specific areas, led to a more concentrated reduction in faecal matter, whereas randomised selection spread the impact more evenly across the city. This analysis demonstrates that management strategies need to be adaptable depending on local circumstances to effectively reduce faecal flow (Muoghalu et al., 2023).

The dynamics of faecal sludge movement in the drain network are influenced by sludge exports through scraping (Fig. S3). These factors contribute to spatial variability in faecal movement (Peal et al., 2020; Strande et al., 2018). Moreover, the type and density of buildings further influence these dynamics. Faecal matter is generated by all building types—residential, commercial, or mixed-use—but the spatial distribution is significantly impacted by the clustering of commercial areas in urban settings (Fig. S4). Commercial clusters often lead to localised increases in faecal sludge production, especially when public sanitation facilities are available, which is consistent with findings from (Strande et al., 2018). Conversely, areas lacking such facilities may contribute less, demonstrating the influence of infrastructure availability on overall faecal flow.

The collective Influence of all factors was evaluated to understand their combined effects on faecal flow across the city (Fig. 5). By comparing these scenarios to the base case model (Fig. 1), the results clearly demonstrate that combining different management strategies leads to significant reductions in faecal flow. Specifically, integrating soak pit adoption with increased septic tank emptying showed reductions of 45 % to 52 % compared to the base case (Fig. 5). This analysis underscores the substantial benefits of an integrated approach to sanitation management, where multiple strategies work in tandem to enhance overall system performance, providing empirical support for holistic practices like those in the Sanitation Cityscape framework (Scott et al., 2015; Willetts et al., 2020).

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 (Saltelli et al., 2020). 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 (Fig. 5c). The analysis of various scenarios (Fig. 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 and 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 and Cotton, 2020) and (Lüthi et al., 2020).

4.3. Practical implications

This study highlights the value of identifying and analysing spatial variations in faecal flow for improving sanitation management.

The study reveals that while individual interventions such as septic tank emptying or improved soak pit usage may only marginally impact faecal accumulation, their combined effect can reduce total faecal flow by up to 50 %. This highlights the need for integrated, multi-component sanitation strategies, echoing recommendations from the WHO-UNICEF Joint Monitoring Programme (UNICEF/WHO, 2023), which advocates for progressive steps toward safely managed sanitation. The accumulation of faecal matter in open drains in this context reflects a widespread reliance on what JMP defines as limited or unimproved sanitation services, where waste is not safely contained, transported, or treated. Our spatial modelling highlights priority areas where targeted interventions can help shift cities upward on the sanitation ladder, toward basic or safely managed services.

The findings align with the Sanitation Cityscape and City-Wide Inclusive Sanitation (CWIS) frameworks, emphasising the need for holistic and context-sensitive approaches to urban sanitation management (Schrecongost et al., 2020). Moreover, the spatial factors identified here offer a practical way for local authorities to conduct targeted field investigations, gather relevant data, and integrate these insights into their service delivery systems.

This research also contributes to advancing wastewater surveillance efforts. By mapping faecal flow patterns, authorities can focus surveillance efforts on areas with higher faecal load concentrations, thereby enhancing the efficiency of monitoring systems and supporting early detection of health risks, such as pathogen spread (Jakariya et al., 2022).

4.4. Challenges, limitations, and future research needs

This study faced significant challenges related to data constraints and the inherent complexity of urban sanitation systems. The reliance on secondary data and anecdotal evidence, although necessary, introduces uncertainties that limit the precision of the model. Preliminary field observations indicate an ~80 % match between predicted and observed faecal flow directions, which lends credibility to the model (Sultana et al., 2025). However, key factors like septic tank size, design, and faecal production rates require more detailed empirical data for validation.

Geological and seasonal factors represent critical dimensions that could influence the functionality of soak pits, such as soil permeability and flooding during monsoons. While these factors were beyond the scope of this study, they are vital for future research, particularly in rural and low-income urban contexts (Mbae et al., 2024).

To build more robust models, future efforts should prioritise validating key assumptions through field surveys and the integration of real-world observations. These steps will strengthen the reliability of faecal flow modelling and support the development of proactive, evidence-based sanitation strategies tailored to the specific needs of unsewered urban areas.

In parallel, future research may explore the use of advanced statistical techniques, such as Monte Carlo simulations, to assess multiple sources of uncertainty within a probabilistic framework (e.g., Cristiano et al., 2020; Wang et al., 2016). The application of higher-resolution spatial data and field-based mapping will further improve the model's ability to capture micro-scale variations, especially in densely populated or poorly mapped areas (X. Li et al., 2020). In addition, collecting empirical data on septic tank operational practices and faecal production rates across diverse urban contexts will enhance model accuracy and relevance.

5. Conclusions

This study assessed the uncertainties of a spatial faecal flow model which showed the sources and the pathways of faecal movement in unsewered cities in Bangladesh. This research provides a foundational understanding of the spatial dynamics of faecal matter movement in unsewered urban settings. Five major influencing factors: septic tank emptying, soak pit usage, sludge removal from drains, faecal matter production variations by building type, and toilet availability —were identified as critical drivers of spatial variability in faecal flow. The findings indicate that the targeted intervention can collectively reduce faecal flow by approximately 50 %, while individually these factors may appear to have a negligible impact. However, this finding reinforces the need for a more advanced, spatially informed approach to sanitation management in unsewered cities. This 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 provides a foundational understanding of the complex spatial dynamics of faecal matter movement in unsewered urban settings, marking a significant step toward effective, proactive, and data-driven sanitation management aligned with SDG 6.2 and 6.3. Future research should focus on validating and scaling this methodology while accounting for the unique spatial characteristics of different urban environments. As many developing cities face similar challenges with limited data, city authorities can leverage the insights from this study to identify critical spatial variabilities and improve sanitation management, potentially informing broader urban planning and public health initiatives.

CRediT authorship contribution statement

M Sufia Sultana: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Toby Waine:** Writing – review & editing, Supervision. **Niamul Bari:** Writing – review & editing, Data curation. **Sean Tyrrel:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT (by OpenAI) in order to assist with language refinement, and improving clarity. After using this tool, the author(s) thoroughly reviewed and edited the content as needed and take(s) full responsibility for the final content of the publication.

Declaration of competing interest

We have nothing to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179440.

Data availability

Open-souece data has been used and appropriet links and references provided.

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