



Sanitation infrastructure and faecal flow – SanIFFlow: A spatial mapping tool for integrated planning and management of sanitation in unsewered urban areas

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ABSTRACT

Proper sanitation is vital for public health, particularly in urban areas. However, planning and managing sanitation systems in secondary cities within economically developing countries presents persistent challenges, largely 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 focused on a city-scale, ward-level model. SanIFFlow provides an actionable insights into infrastructural attributes and faecal flow dynamics, tailored to the practical governance capacities of the city's existing management framework. By leveraging open-source data on buildings, population, and drainage network, the method offers a detailed spatial representation of faecal matter sources and movement pathways within urban catchments. This approach enables strategic sanitation planning and proactive management, identifying high-risk areas and supporting targeted interventions, such as ward-level infrastructure upgrades. SanIFFlow represents a scalable, data-driven tool designed to enhance urban sanitation management in resource-constrained settings.

1. Introduction

Urban sanitation management, especially in unsewered areas, poses persistent challenges that impact public health and urban sustainability [17,26,27]. Despite significant efforts, there remains a critical need for new approaches that enhance spatial understanding and support effective faecal sludge management across diverse cityscapes. The complexity of urban sanitation systems necessitates methods that not only represent faecal flow but also align with the operational capacities of city authorities.

In many secondary cities, the lack of centralised sewerage networks has led to a reliance on onsite sanitation systems, such as septic tanks and pit latrines, which are often poorly managed and frequently discharge into open drains [17,29,3]. These open drains and onsite systems together function as de facto sanitation infrastructure, unintentionally facilitating faecal flow through the urban environment. This unregulated movement of faecal matter poses serious public health and environmental risks, highlighting the need for spatially explicit methods to map and manage sanitation flows.

Existing tools like the Shit Flow Diagram (SFD) provide valuable estimation for entire cities faecal waste flows but often overlook contextual aspects within the city [17,18]. Models such as the 'Sanitation Cityscape' [25,24] and frameworks like CLUES [14] highlight the importance of community-led and household-centred approaches but can be complex, resource-intensive, and challenging to adapt to broader spatial needs. Frameworks such as Citywide Inclusive Sanitation (CWIS) aim to establish equitable, safe, and sustainable solutions, particularly for vulnerable urban populations [23]. However, implementing CWIS has been hindered by challenges, including data limitations, financial constraints, and integration into planning and policy [8,13]. A recent study by Sultana et al. [27] presented a sub-catchment model capable of assessing faecal production and its movement at the building level using open-source data. However, implementing and scaling-up such a detailed model is currently impractical due to resource constraints and the limited availability of service delivery data from the city corporation [17,29,7]. While there have been advances in sanitation research, gaps remain, particularly in the integration of spatial representation and practical applicability.

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These approaches underscore the need for a standardised, scalable methodology that integrates spatial and operational considerations to inform effective sanitation planning.

Sultana et al. [27] previously demonstrated a small-scale spatial representation of faecal sources and movement at the sub-catchment level, covering 0.31 km² in Rajshahi city (Fig. 1). Faecal production was estimated at the building level, with its movement modelled along smaller engineered drains, all ultimately discharging into a larger drain. The sub-catchment, part of the city's larger western catchment, contained ~900 buildings housing ~9000 people. Several such sub-catchments collectively formed the western catchment, with most aligning with ward boundaries, though exceptions exist. While this detailed representation provided valuable insights, its scalability was constrained by data and resource limitations [28].

To address this, we propose SanIFFlow (Sanitation Infrastructure and Faecal Flow) as a scalable spatial analysis framework for urban sanitation planning. SanIFFlow follows a fractal approach, where the same spatial representation principles applied at the sub-catchment level [27] are scaled up to the ward level, preserving fine-scale spatial insights while enabling broader urban analysis. The approach leverages open-source data and aligns with municipal governance structures, making it adaptable to diverse urban contexts.

This paper details the development and application of SanIFFlow, demonstrating how it can be used to map faecal flow, identify high-risk areas, and support targeted sanitation interventions at the ward level.

By integrating GIS-based spatial analysis with urban sanitation planning, SanIFFlow offers a scalable and adaptable framework that can guide data-driven decision-making in secondary cities. The framework is particularly relevant for economically developing cities in the Global

South, where data constraints, resource limitations, and fragmented sanitation infrastructure present significant planning challenges.

2. Study area and data

2.1. Study area

The study was conducted in Rajshahi, a prominent metropolitan city in Bangladesh, known for being an urban, commercial, and educational hub. Located on the north bank of the Padma River and close to the Bangladesh-India border, Rajshahi spans 30 wards over an area of approximately 90 km², supporting a population of around 0.8 million people [1,31,5].

The urban area was divided into eastern and western catchments for the purposes of this study, guided by hydrological analysis conducted in GIS. Each catchment comprises several sub-catchments that help delineate the flow of wastewater within the city (Fig. 1). This study focused on the western catchment, which encompasses 19 of the 30 wards and covers approximately 25 km² [3]. This catchment was chosen to align with the city's operational scale, making it suitable for developing the ward-level SanIFFlow model. The drainage system, consisting of both natural and engineered channels, flows from the south to the north and eventually merges into the Baranai River, a tributary of the Brahmaputra [6]. Inevitably, the waste water ends up in the river.

Sanitation practices in Rajshahi reflect the challenges of unsewered urban areas. Onsite sanitation systems are prevalent, with 80 % of residents using septic tanks—while the remainder rely on pit latrines [31]. Notably, two-thirds of the septic tanks discharge into open drains, contravening the Bangladesh National Building Code (BNBC) guidelines,

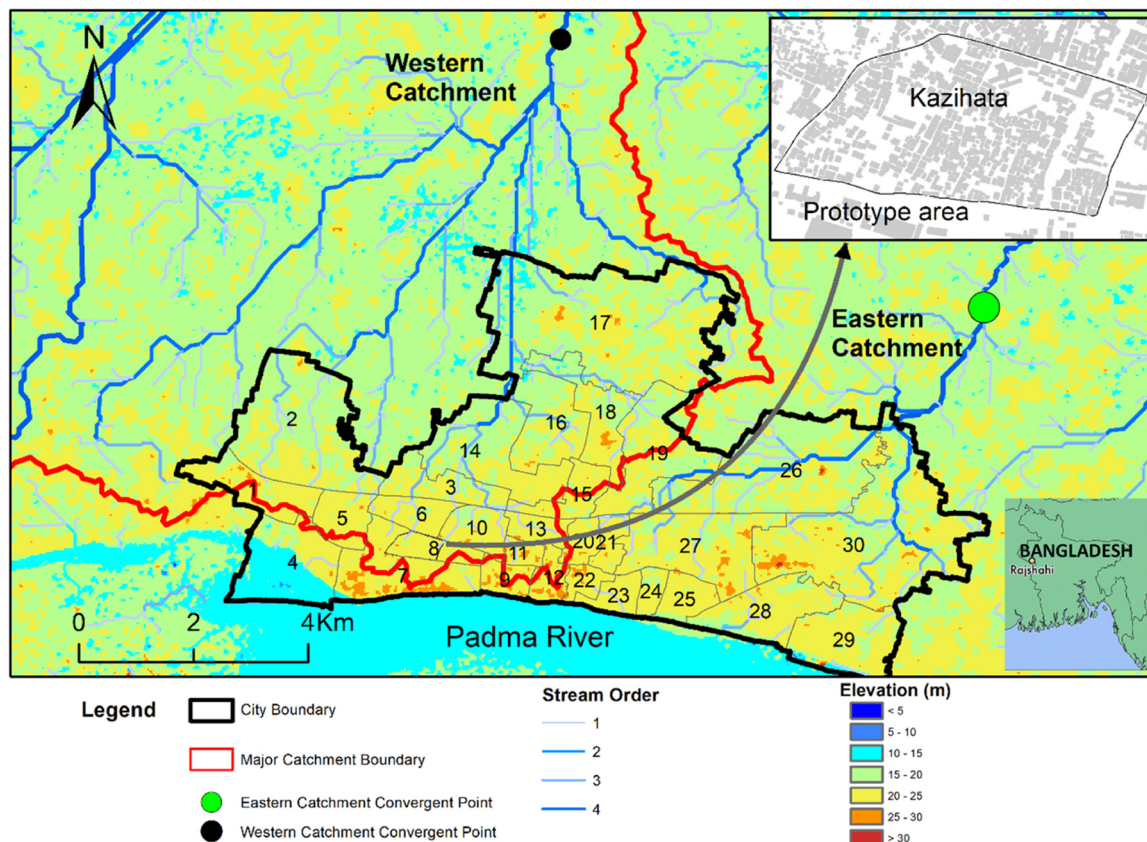


Fig. 1. Spatial context of the study area in Rajshahi, Bangladesh, showing the ward boundaries and the two major drainage catchments: eastern and western. These catchments contain several smaller sub-catchments, visible through the Strahler stream order, which reflects the topographically driven flow direction sloping northward—away from the Ganges (Padma) River. The western catchment, where this study is focused, comprises 19 wards (shown in numbered boundaries) and forms the core of the analysis. A highlighted sub-catchment within the western catchment was previously studied at the building level for faecal generation and movement [27]. In some cases, ward boundaries align with sub-catchment hydrological divisions.

which only 10 % of systems meet [1,29]. Pit latrines typically have open bases, allowing fluid to seep into the ground and, during overflow, into the drainage network [31]. The absence of a sewerage system necessitates effective sanitation management tools that can integrate existing infrastructure and practices.

Recent improvements in water supply have been significant, with the Rajshahi Water Supply and Sewerage Authority (RWASA) established in 2010 to provide clean water to 84 % of the population, primarily from groundwater sources [21]. However, faecal sludge management remains limited, with only one 2,000-litre vacuum tanker (vacutug) available, collecting sludge for transport to an informal dumping site on the city's northern edge. This constrained capacity managed to empty just 30 septic tanks per year by 2017 [1,2].

This study builds on the city's current sanitation framework to develop the SanIFFlow model at a ward level, aiming to provide a scalable and practical tool for urban sanitation management. By focusing on ward-level analysis, the model aligns with Rajshahi's administrative practices, enabling better identification of high-risk areas and supporting targeted interventions.

2.2. Data

This study relies on open-source data to develop and implement the city-wide sanitation model. Key data requirements included building height and area, gridded population estimates, and drainage network data. Building height and area data were derived from remote sensing, allowing for the calculation of building volumes to allocate population proportions effectively. Gridded population data provided the basis for estimating population distribution, which was subsequently aggregated to the ward level [27]. Drainage network and ward boundary data were obtained from the city corporation; the drainage data were filtered to include only major drains, which serve as the primary pathways for faecal flow.

While this approach highlights the adaptability of the model, it also underscores the challenges associated with data constraints. The process would be significantly streamlined if ward boundary data, ward-level population data, and drainage network data were readily available. Access to these datasets would eliminate the need for extreme calculations such as building height, gridded population redistribution, reducing complexity and improving efficiency.

By leveraging open-source data, this study demonstrates the model's capacity to operate in resource-constrained environments while

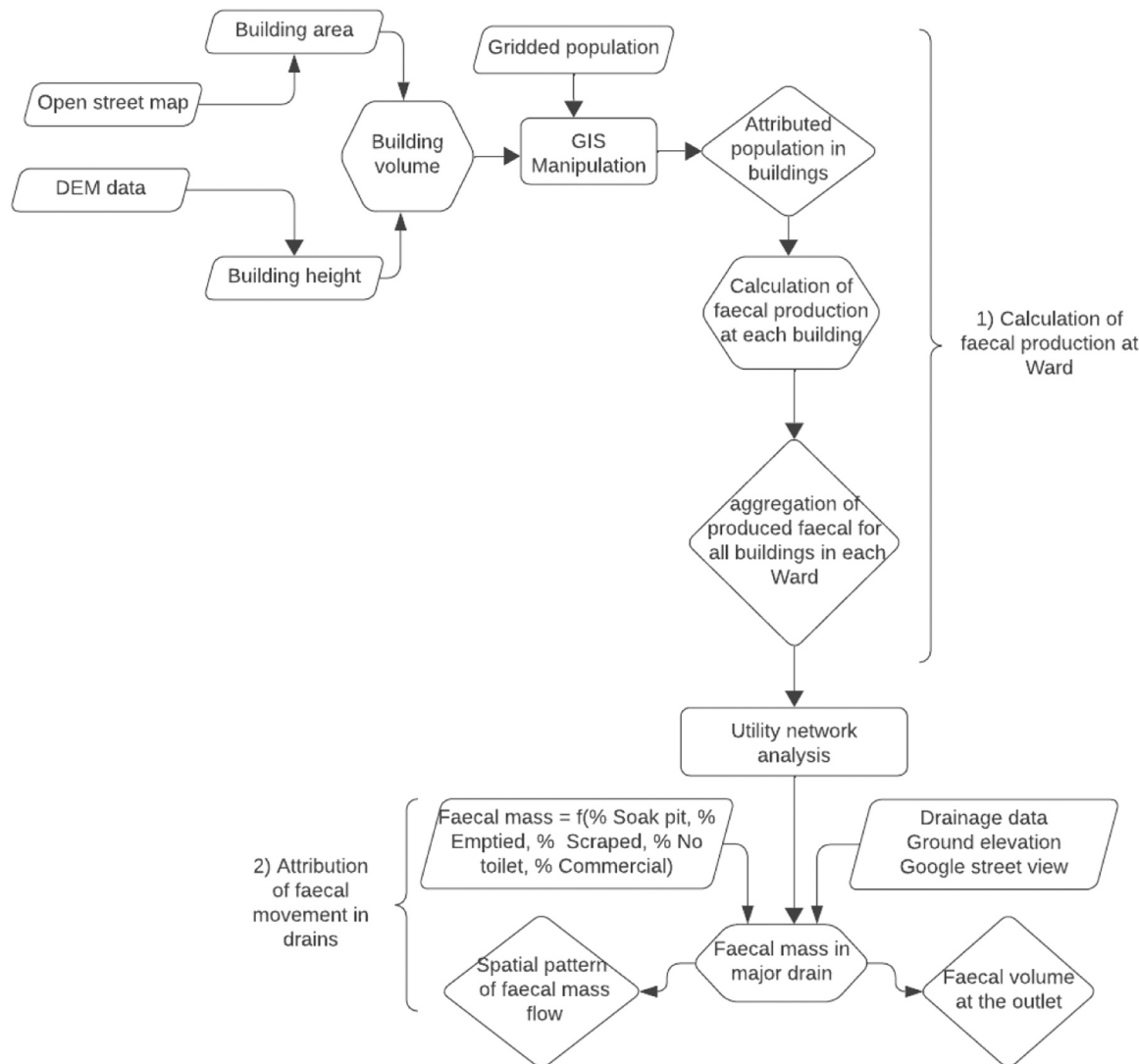


Fig. 2. Flow diagram for the method of ward-level model. There are two important steps: estimation of faecal production in wards and attribution of faecal movement in drains. The symbols used are conventionally applied: the rectangle represents a process, the parallelogram represents data integration, the hexagon indicates preparation steps, and the diamond signifies decision points.

highlighting the potential for enhanced accuracy and simplicity if detailed ward-level data were available. This flexible, data-driven methodology lays a foundation for urban sanitation planning, adaptable across diverse urban contexts.

3. Method

3.1. Estimating faecal production

Faecal production at the ward level was estimated through a sequential process involving population assignment to buildings, calculation of building-level faecal production, and aggregation at the ward scale (Fig. 2). Gridded population data [20] were attributed to individual buildings using a GIS-based dasymetric method [11], ensuring that population distribution reflects building characteristics rather than uniform grid-based assumptions.

The following paragraphs detail the specific calculations for building volume, population distribution, and faecal mass estimation.

Building footprints and heights derived from OpenStreetMap [16] and elevation data from the ALOS PALSAR 12 m Digital Elevation Model (DEM) were used to calculate building volumes. The highest elevation value within each building polygon was extracted to represent the roof elevation, ensuring accuracy by mitigating digitisation errors and mixed-pixel effects [33]. The ground elevation was derived from the lowest elevation value within a 100 m buffer surrounding each building polygon, ensuring that open ground pixels (e.g., roads, empty plots) were included. The height of each building was then computed as:

$$H = E_{\text{roof}} - E_{\text{ground}} \quad (\text{i})$$

where: H = Building height (m).

E_{roof} = Maximum elevation within the building polygon (m).

E_{ground} = Minimum elevation within the surrounding 100 m buffer (m).

This process was systematically applied across all buildings within each ward rather than using selective representative samples or making general assumptions. The total building volume in each grid cell was then calculated as:

$$V_{\text{total}} = \sum_{i=1}^n A_i \times H_i \quad (\text{ii})$$

where:

V_{total} = Total building volume in a given grid cell (m^3).

A_i = Footprint area of building i (m^2).

H_i = Height of building i (m).

n = Number of buildings in the grid.

The population per unit volume was then estimated as:

$$D = \frac{P}{V_{\text{total}}} \quad (\text{iii})$$

where:

D = Population density per unit volume (people/ m^3).

P = Total population in the grid cell (people).

V_{total} = Total building volume in the grid cell (m^3).

Finally, the population assigned to each building was calculated as:

$$P_i = D \times V_i \quad (\text{iv})$$

where:

P_i = Population assigned to building i (people).

V_i = Volume of building i (m^3).

This method ensures that larger buildings accommodate more people, reflecting real-world population distribution patterns rather than applying a uniform assumption across all buildings.

Once population estimates were assigned to buildings, faecal mass production (F) was calculated as:

$$F = P \times R \quad (\text{v})$$

where:

P = Population assigned to the building (people).

R = Per capita faecal production rate (kg/day per person).

Based on previous studies [15,19], a value of $R = 0.25$ kg/day/person was used. The annual faecal mass (F_{annual}) was then calculated by multiplying by 365 days and converting to metric tons:

$$F_{\text{annual}} = P \times R \times \frac{365}{1000} \quad (\text{vi})$$

where:

F_{annual} = Annual faecal mass per building (tons/year).

365 = Days per year.

1000 = Conversion from kg to metric tons.

Ward-level faecal mass estimates were then obtained by aggregating building-level values across each ward.

$$F_{\text{ward}} = \sum_{i=1}^n F_i \quad (\text{vii})$$

where:

F_{ward} = Total annual faecal mass in the ward (tons/year).

F_i = Faecal mass produced by building i in the ward (tons/year).

n = Number of buildings in the ward.

This approach enabled us to quantify faecal load and its spatial distribution within the ward.

However, if ward-level population data is directly available, the model can bypass the building-level aggregation, providing flexibility in areas with varied data availability.

3.2. Determining faecal movement pathways

This city-scale model focuses on primary drains within each ward, which serve as the main pathways for faecal matter movement (Fig. 2). There are mainly three types of drains in the city [28]. Primary drains are the main drain in the area, serving as the principal conduits in the locality, and 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 [29,9]. These primary drains are larger, uncovered, and designed for high capacity, contrasting with local tertiary and secondary drains that are connect to individual buildings. Primary drains have often been modified from natural topographic depressions to engineered channels with concrete walls to enhance durability and capacity [12].

By prioritising primary drainage channels, this model shifts from a localised view of interconnected drains to a broader, city-wide perspective. This approach provides a broader perspective on faecal movement dynamics at the ward level, offering insights that can support urban sanitation management.

3.3. Ward to drain connectivity and sankey representation of faecal movement

This study adopts a ward-level approach, using ArcGIS-based proximity analysis to link the geometric centroid of each ward (assumed as the location of faecal production) to the nearest main drainage channel. The centroids were computed using the "Feature to Point" tool in ArcGIS, ensuring that each centroid remained within its respective ward boundary. While this method assumes that all faecal matter produced within a ward flows into its primary drain, in reality, tertiary and

secondary drains first carry faecal flow before it reaches the primary drain [28]. Additionally, some buildings may discharge into a different primary drain than the one assigned by our simplification, though these cases are limited. This assumption remains a practical abstraction for city-scale sanitation planning.

Flow direction in each primary drain is determined using a combination of GIS-based natural slope analysis, engineered drain data, and supplementary Google Street View observations, where available. Slope analysis was conducted using a 12m-resolution ALOS PALSAR Digital Elevation Model (DEM) in ArcGIS, applying the "Flow Direction" tool to determine primary drainage pathways. However, since the DEM captures building rooftops rather than the actual ground surface, elevation corrections were necessary to avoid misleading slope calculations. To retrieve the true ground elevation, we created a 100 m buffer (~8 DEM pixels) around each building. Within this buffer, the minimum elevation value was extracted under the assumption that at least some pixels would represent open ground, such as roads or empty plots. These low-elevation values were then rasterized to reconstruct a corrected ground surface i.e. digital surface model (DSM), which was subsequently used

for slope calculations. This process ensured that drainage pathways reflected the natural topography rather than artificial height distortions caused by buildings (Figure 7 in [28]). The resulting drainage network map highlights the connectivity between faecal production sources and their associated primary drainage pathways.

A Sankey diagram [22] is employed to visually represent faecal matter flow through the city's primary drainage system. In this diagram, the width of the lines corresponds to the estimated mass flow, offering an intuitive and scalable tool for visualising high-risk areas and prioritising interventions. The mass flow at each drainage segment was derived by aggregating ward-level faecal production estimates and assigning them to their respective drainage pathways based on proximity and flow direction analysis.

4. Results

4.1. Population distribution in wards

In the model (Fig. 3), the population was first distributed among

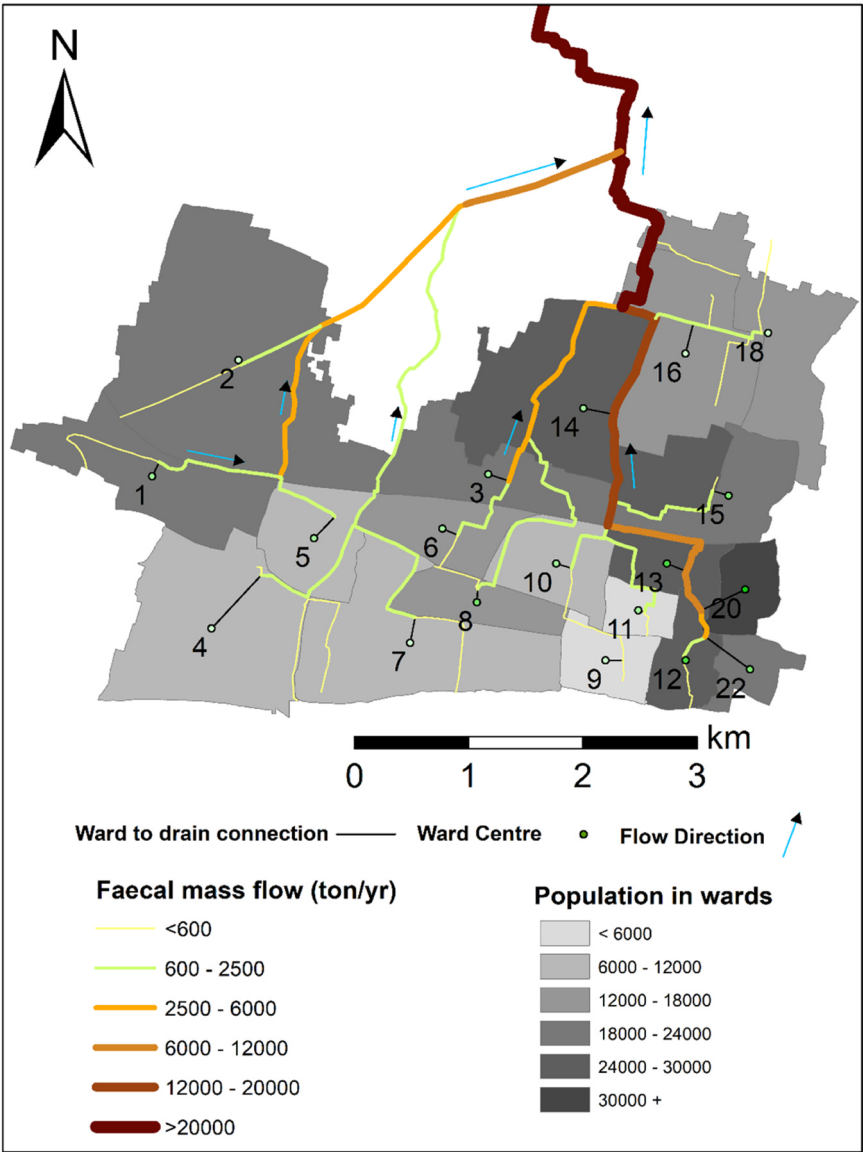


Fig. 3. Faecal mass flow in the western catchment, moving northward toward the outlet, derived from ward-level faecal mass production. The map shows each ward connected to the nearest primary drain. The mass flow variations depend on the population in each ward and faecal contribution from upstream areas. Faecal mass flow in the western catchment, moving northward toward the outlet, derived from ward-level faecal mass production.

buildings and then aggregated into wards, with each ward containing approximately 1300 to 5,000 buildings and hosting 15000 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 6000, to the darkest shade representing wards with a population as high as 43,300.

4.2. Faecal production at wards and their pattern

Fig. 3 illustrates the spatial distribution of faecal mass flow within the western catchment of Rajshahi city, which is 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 amount of faecal mass (Eq. vii) ranges between 1190 and 2940 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.

4.3. Faecal movement and Sankey representation

The Sankey diagram (Fig. 3) 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 mass of faecal material being transported: thicker lines indicate higher masses, 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 using the Natural Breaks (Jenks) classification method. This approach groups data values into classes by minimizing variance within each class while maximizing variance between classes, ensuring that the classification reflects the natural distribution of faecal mass across the study area.

For example, a faecal mass flow of 600 tons per year represents areas with lower population densities, which are typically located in the headwater parts of the catchment. These areas mark the initial stages of the drainage network, where faecal accumulation is lower due to fewer contributing households. As runoff and waste from multiple upstream sources converge, faecal mass increases further downstream, forming higher-classified zones in the GIS representation. The classification scheme, therefore, captures both population-driven faecal contributions and hydrological flow patterns, allowing for a meaningful spatial representation of sanitation risks.

Conversely, the northernmost part class summarises 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. Discussion

5.1. Interpretation of the movement of faecal matter

The study indicates a direct correlation between population density and faecal matter dynamics in Western Catchment area of Rajshahi city. The northward increase in faecal accumulation, as depicted by the spatial analysis and the Sankey diagram (Fig. 3), highlights the accumulative nature of faecal flow in downstream areas. Considering hydrological profile of the city, with a higher elevation in the south and a drainage network predominantly flowing northward [6], 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 role of primary drains in transporting significant quantities of faecal matter, and the associated risks of flooding and blockages, is a major concern for urban sanitation management [4]. 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 accuracy of the model. 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 [32].

The city-scale model demonstrates spatial variability in faecal matter production, with eastern part of the map, 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. The importance of the field validation has been demonstrated in Sultana et al. [28] for sub-catchment level representation of sanitation infrastructure and faecal flow. Nevertheless, the model is instrumental in identifying priority areas for sanitation infrastructure improvement.

5.2. Operational frameworks and spatial considerations

Effective sanitation planning requires an understanding of faecal production and movement across different spatial scales. Existing approaches typically assess sanitation at either the entire city, which provides an overarching view of the sanitation service chain [18], or the sub-catchment model, which captures faecal production and movement at buildings level [27]. While both scales offer valuable insights, neither fully meets the operational needs of city authorities.

Building on recent sub-catchment analyses [27], this study scales up the model to a city-wide, ward-level approach, covering 19 wards in the western catchment. This fractal transition enhances the feasibility of large-scale sanitation management while maintaining the spatial representation principles applied at the sub-catchment level. The structured approach aligns with infrastructure planning and sanitation service provision [27,28]. By initially applying the ward-level model for broader sanitation planning and integrating the sub-catchment model when greater detail is required, SanIFFlow (Sanitation Infrastructure and Faecal Flow) offers a structured, scalable approach for unsewered urban sanitation management. The ward-level model aligns well with municipal governance structures, making it practical for large-scale decision-making. However, while it provides an overarching view, it

may lack the granularity needed to capture localised sanitation challenges [28]. When more detailed insights are necessary, the sub-catchment model, based on building-level analysis, can be employed to refine interventions, enabling targeted sanitation improvements. Despite its advantages, implementing the sub-catchment model city-wide is challenging due to high data requirements, financial constraints, and administrative limitations [10]. By combining range of spatial representation scale, SanIFFlow provides flexibility, allowing cities to balance large-scale planning with detailed, localised assessments where necessary.

5.3. 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 [14,25,24]. Despite the lack of systematic record-keeping by these authorities, the reliance of model on open-source data and its essential assumptions could be significantly enriched if municipal activities were documented and integrated (Table 1).

The spatial scale of the city sanitation system is critical, as wards are interconnected within a hydrological hierarchy, where upstream conditions directly influence downstream sanitation dynamics. 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 [28]. A ward-level SanIFFlow approach, involving data collection and fine-scale models [27], can be more effective, as identified wards with significant sanitation challenges can be addressed through greater data collection effort. 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 by scraping the accumulated sludge (Fig. 2). 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 mass; additionally, sanitation service delivery data can be easily recorded (Table 1), facilitating the development of models that reveal broader patterns and trends in faecal matter flow throughout the city.

Open-source data enables analysis at multiple spatial scales, from household-level assessments to city-wide comparisons, helping to identify service delivery gaps. Mtika, Tilley [14,25,24]. However, systematic records of these services are often lacking, limiting the ability to capture local variations in sanitation management. While this study demonstrates the feasibility of using open-source data, incorporating municipal service records could enhance precision and operational relevance of the model.

A ward-level SanIFFlow approach, supported by structured local data, could improve sanitation oversight by refining estimations of key factors such as septic tank emptying frequency, soak pit prevalence, and drain maintenance (scraping) needs. Despite the hydrological interconnections between wards affecting downstream areas, no standardised visualisation tool currently exists to compare sanitation conditions across different parts of the city. Addressing this gap through targeted data collection would provide city authorities with a more data-driven framework for sanitation planning.

Table 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	Actions needed for data acquisition	How to use the data in SanIFFlow
Septic Tank Emptying Amount (kg/yr)	<ul style="list-style-type: none"> - Municipal or private emptying operator's needs to maintain regular records of the number of septic tanks emptied, e.g., how many trucks from a ward? - Access logs from municipal or private desludging operators. 	<p>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.</p> <p>Use recorded volumes and emptying frequencies to estimate the amount of faecal mass removed from septic tanks. Subtract this from the ward-level faecal production to refine net flow estimates into the drainage system.</p>
Number of Soak Pit (i.e., not connected to the drain network) (Eqv. Faecal mass in 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 based on their volume assuming they operate at full capacities. - Include observations on the prevalence and condition of soak pits in the area. 	<p>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.</p>
Drain Scraping (kg/yr)	<ul style="list-style-type: none"> - Conservancy departments can 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. 	<p>Subtract known quantities of removed sludge from modelled faecal accumulation in downstream drains.</p> <p>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.</p>
Commercial Areas Contribution (Eqv. kg/yr)	<ul style="list-style-type: none"> - Identify and categorise commercial/institutional buildings using local data and field validation. Calculate equivalent faecal mass contribution from commercial areas in kilograms per year. - Note the density and type of commercial activities in the ward. 	<p>Estimate additional faecal load based on average occupancy or workforce size and per capita production rates. Add to overall ward-level faecal generation. Including accurate data on faecal contributions from commercial areas in the model will inform targeted faecal management strategies, optimizing resource allocation and interventions.</p>
Buildings with No Toilet (Eqv. kg/yr)	<ul style="list-style-type: none"> - Use household survey or census data to identify buildings without access to sanitation facilities e. g., warehouse and estimate the equivalent faecal mass not entering the drain. - Observe and note any relevant socio-economic or infrastructural factors. 	<p>Identifying buildings without toilets will help better characterize the spatial variability of faecal production and support targeted management strategies.</p>

While open-source data formed the foundation of this study, certain critical datasets—such as ward-specific sanitation service records—remain unavailable. Table 1 outlines essential sanitation attributes that, if systematically recorded, could enhance the predictive capacity of the model and support better infrastructure planning. A structured data collection framework would enable city authorities to implement more proactive and targeted sanitation interventions, ultimately improving service delivery across the city.

5.4. Integrating SanIFFlow with existing management system

The SanIFFlow approach offers a flexible and scalable framework for urban sanitation management, capable of operating at multiple spatial granularities—from the building level to the ward level—allowing it to integrate seamlessly with existing municipal management systems. While this study focuses on its application within Rajshahi City Corporation (RCC) as a case, the methodology is adaptable to other urban settings, particularly in cities where sanitation service delivery faces similar challenges due to unsewered infrastructure and fragmented data availability.

The organisational structure of RCC, as referenced in Fig. 4 [3], provides an example of how a data-driven approach to sanitation management can be implemented within an existing municipal framework. The Chief Conservancy Officer and supporting staff can facilitate the adoption of SanIFFlow by integrating spatial insights into routine city planning and monitoring. For instance, by identifying drains prone to blockages due to sludge accumulation, local authorities can develop preventative maintenance strategies, reducing long-term operational challenges.

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: 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 (Fig. 4). 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. SanIFFlow provides a structured approach to sanitation management, enabling academic and professional communities to incorporate spatial analytics into decision-making for improved public health and environmental sustainability.

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 utilises 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.

6. 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 [30]. 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

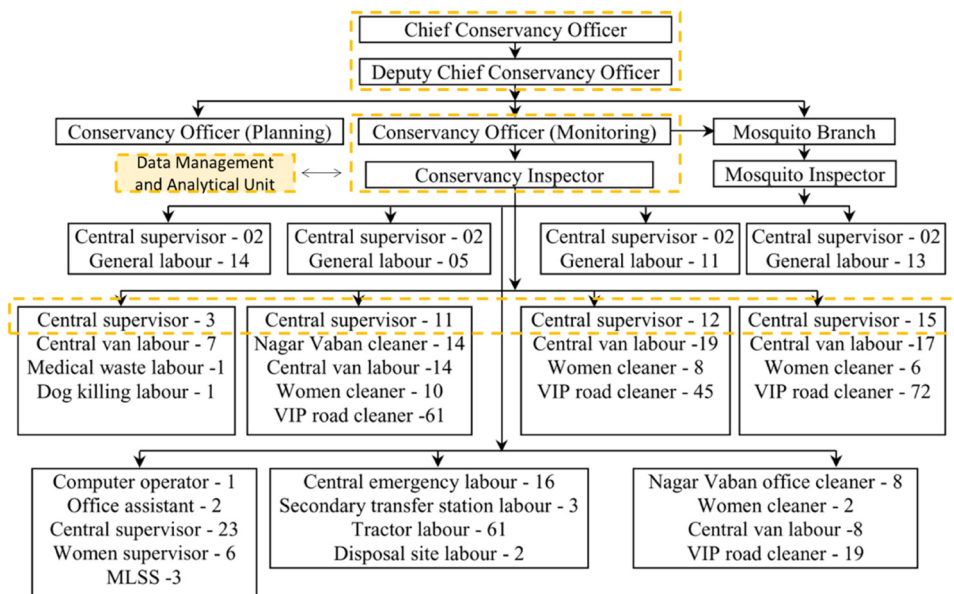


Fig. 4. Organisational structure of the Rajshahi City Conservancy Department, showing personnel distribution across different roles [3]. The numbers indicate the total staff assigned to each category (e.g., ‘VIP road cleaner – 61’ represents 61 personnel cleaning high-priority roads). While the diagram reflects the department’s complexity, the key focus is on the integration of the proposed Data Management and Analytical Unit (highlighted in yellow) within the existing structure. This unit is designed to process data for strategic decision-making and infrastructure planning, enhancing service efficiency.

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 [11], 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. 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. The robustness of this methodology, in light of these limitations, offers a significant contribution to the field of urban sanitation planning and management.

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 unserved 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.

Declaration of Generative AI and AI-assisted Technologies

During the preparation of this manuscript, the authors used OpenAI's ChatGPT to improve language clarity and grammatical correctness. The authors carefully reviewed and edited the content to ensure accuracy and take full responsibility for the final manuscript.

Submission Declaration and Verification

This manuscript has not been published previously and is not under consideration for publication elsewhere. All authors have reviewed and approved the submission and affirm that, if accepted, this article will not be published in the same form elsewhere without permission from the copyright holder.

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CRedit authorship contribution statement

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

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Data Availability

The author has shared the link to the data.

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Sanitation infrastructure and faecal flow – SanIFFlow: a spatial mapping tool for integrated planning and management of sanitation in unsewered urban areas

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