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**Research Paper**

# Towards a new spatial representation of faecal sources and pathways in unsewered urban catchments using open-source data

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## ABSTRACT

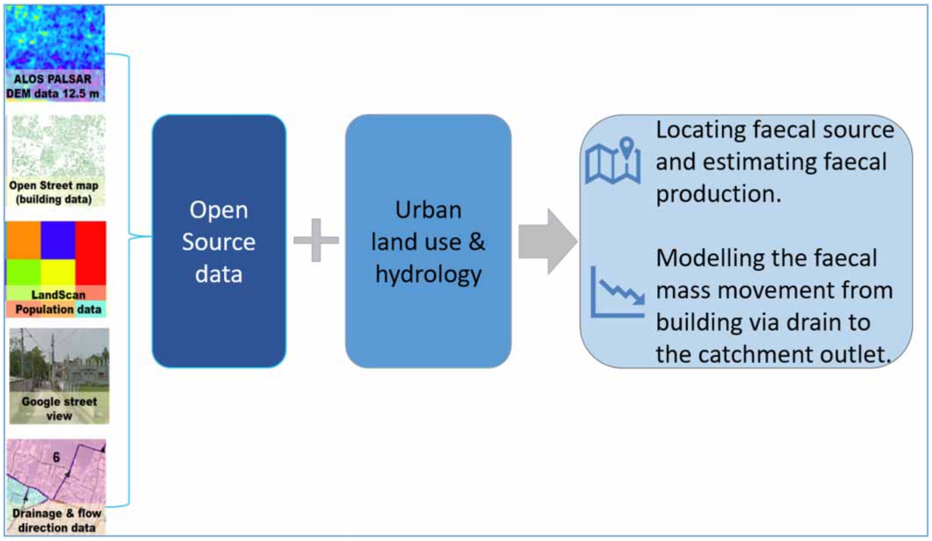
Spatial representation of sanitation infrastructure and service coverage is essential for management planning and prioritising services. The provision of sanitation services in developing countries is inherently unequal because the sanitation infrastructure is lacking, and onsite sanitation is managed individually. Here, we developed a prototype method for creating a spatial representation of faecal sources and movement in a small area in Rajshahi city in northwest Bangladesh, which is representative of 60 other such secondary cities. We demonstrate an approach to estimate spatial variability in faecal production at the building scale by combining widely accessible buildings, ground elevation, and population data. We also demonstrate an approach to attribute potential faecal movement pathways by integrating drainage data, and faecal production at the building scale. We made use of free and open-source data and provide answers to the broader topic of spatial representation of faecal mobility in unsewered urban settings, which has implications in a similar setting in developing countries.

**Key words:** Bangladesh, faecal movement, open-source data, spatial representation, unsewered, urban catchment

## HIGHLIGHTS

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

## GRAPHICAL ABSTRACT




## 1. INTRODUCTION

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

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

Faecal waste is mostly maintained at the individual household level and on an informal basis in these cities, through the use of septic tanks and pits. Septic tanks are often constructed underground, with two chambers, one of which is two-thirds the size of the tank. An inlet pipe transports the faecal matter and flushed water to the bigger chamber, where it is held to separate the liquid and solid waste, allowing supernatant fluid to overflow into the second, smaller chamber, from where it is discharged into the drains via the outlet pipe (Tilley *et al.* 2014). In theory, the majority of the faecal solids should be stored in the tank awaiting emptying and offsite disposal. In practice, a lack of emptying means that faecal solids probably exit the tank to the drain once the tank is full. These drains are therefore carrying all the wastewater throughout the city (Foster *et al.* 2021). The mapping of sanitary infrastructure, including faecal movement in cities, is a data-intensive procedure that necessitates a household-level survey, which is a massive effort due to inadequate management systems, financial resources, and technical competence (Strande *et al.* 2018). For this reason, spatial understanding and mapping capabilities for the sanitation service chain are limited. However, over the Past decade, several free and open datasets (OpenStreetMap

Contributors 2019), and Landscan population data (Rose *et al.* 2020) have emerged, allowing them to be used in a variety of applications (Coetzee *et al.* 2020), for example, a methodology to produce urban functional land use map (Vu *et al.* 2021).

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

## 2. DESCRIPTION OF THE STUDY AREA

Rajshahi is a metropolitan city, and one of the major urban, commercial, and educational centres of Bangladesh. Located on the north bank of the Padma River, near the Bangladesh-India border, the city consists of 30 wards with a total area of ~90 km$^2$ and a home to around 0.8 million people (WaterAid 2018).

The climate of the city is generally marked by monsoons, high temperatures, considerable humidity, and a mean annual rainfall of ~1,500 mm compared to a national average of 2,500 mm (BBS 2005). The surface geology consists mainly of sedimentary formations, mostly riverine in origin. The area has a general slope from south to north with a ground elevation of 17.0–18.0 m Public Works Datum (PWD: ±0.5 m to sea level) in (Figure 1). Although the city is situated on the left bank of the Ganges River (locally known as the Padma) because of the northward slope, the area is drained by a local river called the Baranai – a tributary of Brahmaputra (Dissanayake *et al.* 2007).

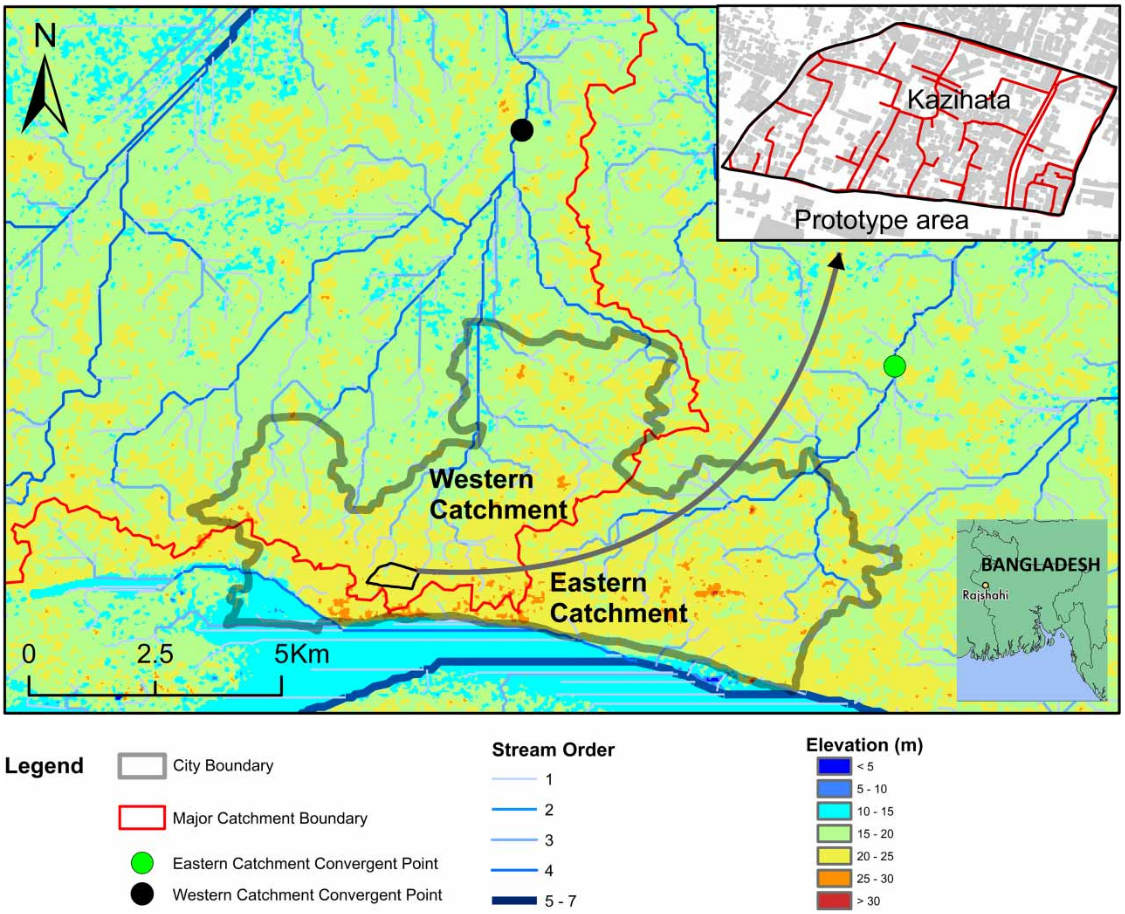



**Figure 1** | Rajshahi city and its catchments along with the prototype area. The city is mostly divided into two catchments: eastern and western. Each of these catchments is composed of several sub-catchments. The prototype area is one of the mini-catchment in a sub-catchment.

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

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

There is one 2,000-l portable vacuum tanker (vacutug) that is used for collecting and transporting faecal sludge from septic tanks to the designated informal dumping site in the northern outskirts, as there is no treatment plant in place (Bari 2017). The uses of the vacutug are limited since it only emptied one septic tank when it first started in 2011 and since has grown in popularity, resulting in the emptying of 30 septic tanks per year as of June 2017 (Bari 2017; Bari *et al.* 2018).

## 3. DATA AND METHOD

A prototype area of 0.31 km$^2$ was chosen conveniently to create the methodology of spatial representation of faecal production sources and pathways. The availability of the Google Street View data was a consideration for choosing the area. The area was considered to be a representative sample of larger areas as it has similar building patterns, such as multi-story residential and commercial buildings, and storm drainage characteristics. This could also generate reliable results that could be generalised to other areas. This sub-catchment has around 900 buildings and most of those are residential multi-storey and home to around 9,000 people. The buildings that are located by the major roads have mixed use with commercial activities restricted to the ground floors with few exceptions where the entire building is commercial or used as a public facility (e.g., schools, hospitals). The area is heavily built-up with a few constructed ponds and open spaces.

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

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

### 3.1. Data

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

### 3.2. Methods

The method consisted of a model that has two connected sub-models: (i) population distribution and faecal production in each building and (ii) building-to-drain connectivity and Sankey representation of faecal movement in drains (Figure 2). Model inputs comprised a combination of estimates based on relevant scientific literature as well as space data collected and analysed from various sources as explained below. Around nine hundred households have been included in the model to predict their expected effect on faecal production and spatial representation of the area. The model also identified the challenges and uncertainties of different scenarios relating to the spatial scale, city's land use, and current sanitation management practices.

(i) Population distribution and faecal production in each building

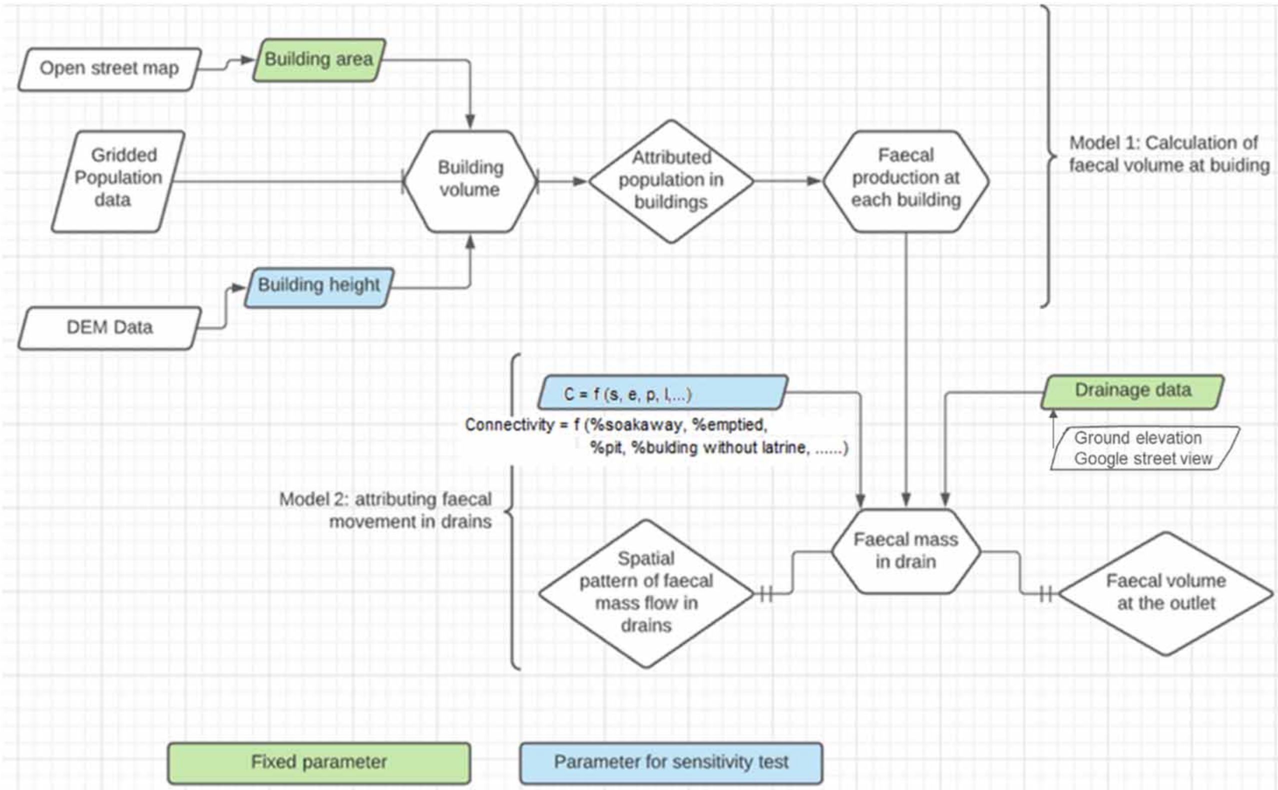



**Figure 2** | Major input parameters in two-stage modelling of the faecal movement analysis.

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

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

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

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

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

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

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

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

The building centre (septic tank) locations are used as sources, while the catchment outlet (receptor) is used as a sink (ESRI 2019). The prototype area has only one sink, which is the catchment's outlet, as determined by the flow direction and the lowest elevated point within the area. The utility network analysis generates the flow direction using basic sources and sink rules. The potential faecal mass conveyed by each drain has been determined using this network. The amount of faecal solids ending up in the drains from individual septic tanks are subject to various factors including the presence of a soak pit, prior emptying, and a building that may not have a toilet in the first place. However, in this case, it was assumed that all produced faecal solids ended up in drains and were considered an indicator of faecal movement. The flow variation in this connected drain network is demonstrated by relating the width of the lines to its flow rate in units of kg/yr using the Sankey concept (Schmidt 2008), and therefore, the diagrams reveal where the focus of mass flow is occurring. A Jenks natural break classification system is used to show the variability as this gives the most optimal class range found 'naturally' in a data set and it seeks to minimise the average deviation from the class mean while maximising the deviation from the means of the other groups (Jenks 1977).

## 4. RESULTS

### 4.1. Buildings and population distribution pattern

The prototype area is mostly covered by one major population grid and intersects with two additional grids. This part of the city is densely populated, with about 20,000 people living in a square kilometre and the estimated population of the prototype area is around 9,000.

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

When the size of the building is considered, the majority of buildings are less than 200 $m^2$, with little variation in building sizes with respect to the area. When height is taken into consideration, however, there is noticeable spatial variability, with taller buildings in the prototype area's centre (Figure 3).

### 4.2. Faecal production at buildings and their pattern

The data reveal that the faecal output varies widely between buildings (Figure 3). In the area, buildings with higher storeys or a greater footprint create more faecal matter as a result of the model assumption that population is directly correlated to building volume. The spatial variation within the prototype area is explained by the height and size of the buildings. Majority of the high faecal producing buildings are located in the centre of the area, which is mostly high-rise buildings while buildings with larger footprint have faecal production of over 5,000 kg/yr. Most of the buildings in the area produced faecal $<$1,500 kg/yr.

### 4.3. Faecal movement and Sankey representation

The Sankey representation shows the faecal mass flow pattern inside the area, where there are three service catchments, with the middle one having higher faecal mass flow due to being more densely populated than the other two (Figure 4). The thinner lines show less faecal mass, whereas the wider lines show more. The inner small lines also represent its width depending on the proportion of faecal mass.

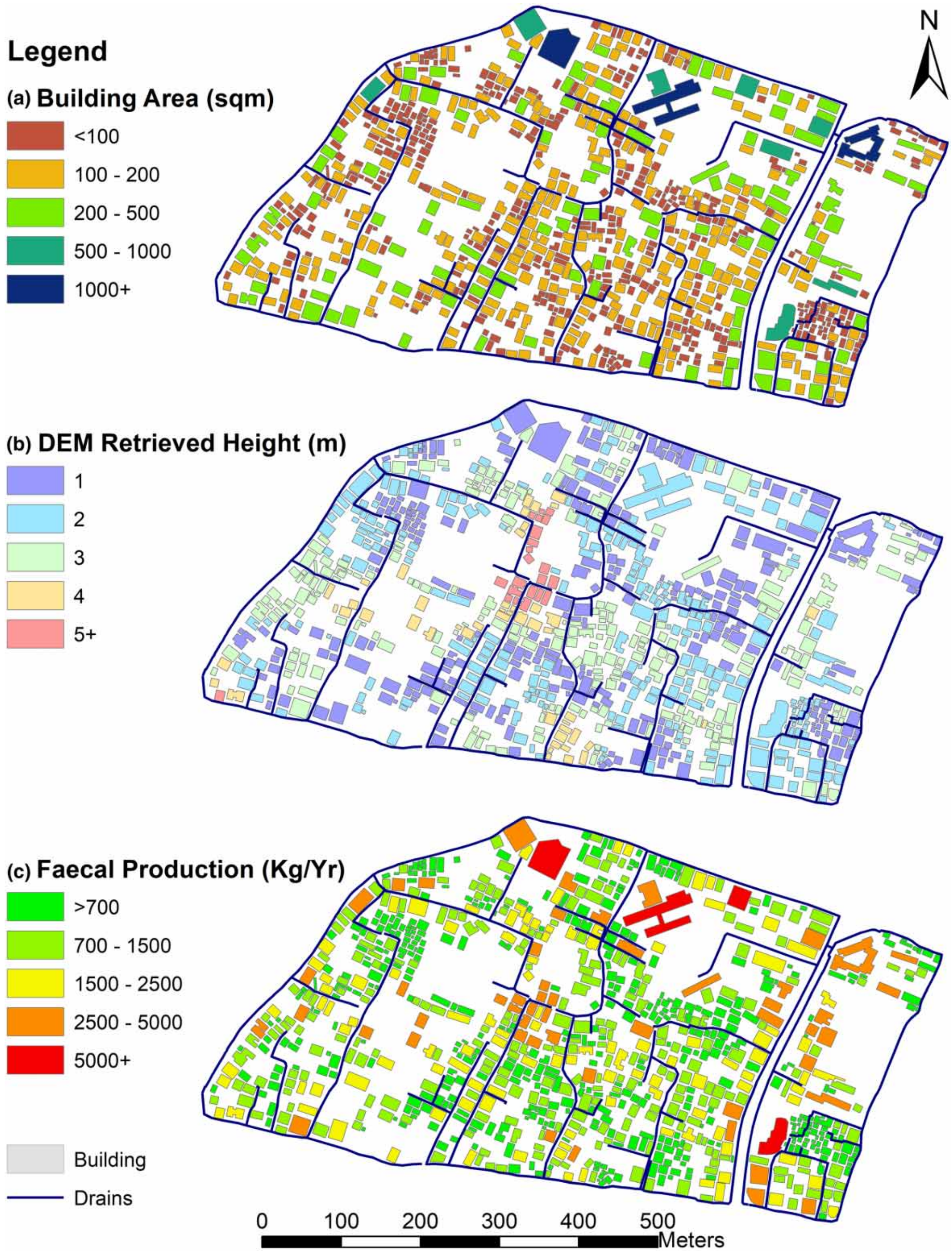



**Figure 3** | Spatial variation of building height (a), area (b), and faecal mass production at each building (c) across the prototype catchment. The distribution of large buildings with faecal mass >5,000 kg/yr is uneven.

## 5. DISCUSSION

### 5.1. Identifying the sources of faecal production and spatial representation

We all know that the source of faecal matter is the population (Strande *et al.* 2018; Englund *et al.* 2020); however, positioning the population, where the faecal produces, and how it will relate to faecal movement pathways is technically challenging, particularly in unsewered environments (Mills *et al.* 2018; Foster *et al.* 2021). This study used building data from an open street map to locate the sources where the building centroid was assumed to be a faecal production location. Normally,


**Figure 4** | Sankey representation of faecal movement. The discharge point, i.e., outlet of the catchment is located in the top of the northeast corner, which is carrying 810 tonnes of faecal mass on a yearly basis. The values were categorised using Jenks natural breaks (with two significant digits rounding) as mentioned in the 'Methods' section.

existing methods of estimating faecal production (Strande *et al.* 2018; Peal *et al.* 2020) take the population and estimate faecal production based on the total population of the entire city. The limitation of this method is that we are unable to determine the places with the highest concentrations of faecal matter, as well as the magnitude of spatial variability. Collecting data at the household level is too labour-intensive, especially in areas where there is no existing information (Peal *et al.* 2014; Strande *et al.* 2018). There is no proven method that exists that can quantify faecal production in urban areas (Strande *et al.* 2018). In order to obtain a good spatial estimate of faecal production, the number of users and the location are important parameters (Peal *et al.* 2014; Strande *et al.* 2018) which we show is possible to estimate using remotely sensed data. However, in this preliminary approach, people were allocated evenly throughout buildings based on their volume, which was a pragmatic arbitrary assumption for the purposes of building a prototype and which will need to be improved in future versions of the model.

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

We used an average of 250 g per person per day faecal matter production (Rose *et al.* 2015) in our estimation of faecal production. In reality, there is likely to be significant variability around this mean in the amount of faecal production which vary between family members (age and gender) and between families because of food habit. In a building there are around 8–10 families, and the faecal production will vary between the individuals. As here we are estimating faecal volume at the building level, the individual variability may be incorporated within the average we took. Therefore, there is a limited possibility of a significant effect on the faecal production estimation.

### 5.2. Identification of faecal movement pathways

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

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

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

### 5.3. Implications and outlook

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

This study is critical for developing a better understanding of the spatial sanitation situation in cities, which will help to reduce the gap in wastewater and FSM prioritising, planning, and decision making. The purpose of spatial representation is to provide a credible approach to locate faecal sources and movement pathways for a better understanding of the potential areas of faecal accumulation. It provides a characterisation and understanding of sanitation system of the city beyond what current tools are capable of, necessary for effective management and prioritisation of resources. Normally, to solve the sanitation issue, city authorities typically handle faecal matter and drains in a reactive manner, only taking action when there is a problem, rather than proactively maintaining the drains to prevent them from being blocked and/or overflowing. This approach is inefficient and ineffective as it does not address the root cause and does not prevent future problems. A proactive approach that tackles both short-term and long-term challenges can be developed by using the spatial representation technique we describe here.

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

## 6. CONCLUSIONS

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

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## DATA AVAILABILITY STATEMENT

All relevant data used in this study are available from online repositories. The LandScan data used in this study is available at https://doi.org/10.48690/1524214. The ALOS PALSAR 12 m digital elevation model data used in this study are available from https://search.asf.alaska.edu/#/?dataset=ALOS. The OpenStreetMap building data used in this study is available at https://planet.openstreetmap.org. Additionally, Google Street View data was used in this study and is available through GoogleMaps at https://earth.google.com (last accessed 20 Dec. 2022). The data used to generate the model are open-source and referenced with citations in the text where they appear.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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