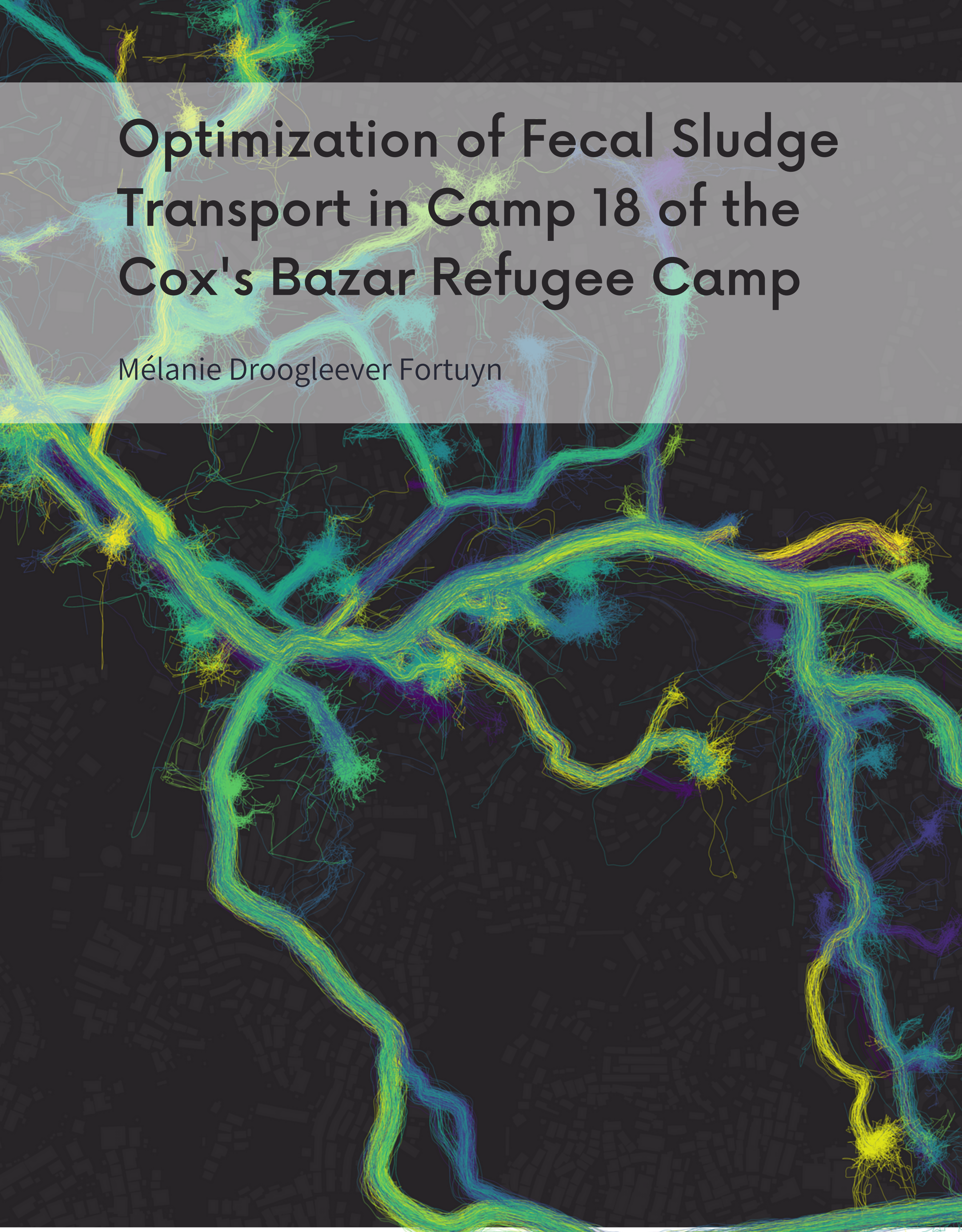

Optimization of Fecal Sludge Transport in Camp 18 of the Cox's Bazar Refugee Camp

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Master's Thesis

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Date

11th of February 2022

Acknowledgments

I want to extend a special thank you to my supervisors, François Golay from the Environmental Sciences and Engineering Section at the École Polytechnique Fédérale de Lausanne (EPFL), Christoph Luthi from the Department of Sanitation, Water and Solid Waste for Development (Sandec) at the Swiss Federal Institute of Aquatic Science and Technology, Christopher Friedrich from Sandec, and António Antunes from the Department of Civil Engineering, University of Coimbra, Portugal.

Additionally, I want to thank Shafiur Rahaman for carrying out all the field activities, as well as Tanoy Dewan and Kurt Saygin for transporting the GNSS data loggers to Bangladesh.

Finally, this research was made possible with the support of the Bangladesh Red Crescent Society and the Swiss Humanitarian Aid Unit.

Abstract

Sanitation planning and management is a complex problem, especially in emergency contexts such as refugee camps. Camp 18 of the Cox's Bazar refugee camp has over 27 000 inhabitants, who have access to 1931 latrines from which the sludge is treated in a centralized fecal sludge treatment plant. However, with 9 % of residents reporting full latrines and manual sludge transport providers struggling to service all the latrines, new approaches and insights are needed to improve this fecal sludge management system. Therefore, this thesis aimed to investigate and optimize the service coverage of the camp's fecal sludge transportation system. Firstly, 24 spatial data loggers were attached to the sludge transport barrels to examine the successes and downfalls of the current fecal sludge management system. This spatial data was supplemented with interviews with the desludging team to understand the motivation behind certain decisions. The resulting insights were used to design an optimization model aiming to minimize transportation distance and elevation change. The results of this research highlight the value of spatial data collection when investigating and optimizing large-scale complex systems in emergency contexts. Furthermore, it provides insights into the unique and complex nature of a publicly managed, manual transport, fecal sludge collection system within a refugee camp.

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1 Introduction

The United Nations High Commissioner for Refugees (UNHCR) currently estimates that there are 21 million refugees globally, who are defined as people fleeing war, violence or persecution [1]. With this number growing annually, refugee camps are expanding and new camps are being created. Some of these camps are densely inhabited and require the emergency set-up of basic services, such as waste management, that are strategically planned [2]. With almost 50 % of the global population living in cities, the provision of basic services within densely inhabited environments is a common topic of discussion [3]. While efforts are focused on ensuring infrastructure is built to meet the service requirements of the population, less emphasis is placed on the management of these services [4]. Specifically, the adequate management of waste can have a large impact on the welfare of humans and the environment. Fecal sludge is one such waste stream in refugee camps that requires transportation from public latrines to fecal sludge treatment plants, often managed by humanitarian aid organizations.

Cox's Bazar refugee camp is home to over 860 000 Rohingya refugees that fled ethnic and religious persecution in Myanmar [5]. This thesis will specifically address the struggles with sanitation experienced by the approximate 27 000 inhabitants of Camp 18 within the refugee camp [5]. Camp 18 is managed by the Bangladesh Red Crescent Society (BDRCS), which was a key partner for this thesis. The fecal sludge produced by Camp 18 residents is collected within latrines managed by the BDRCS. Desludging teams then use pumps to empty these latrines into transportation barrels and manually carry them to the camp's fecal sludge treatment plant (FSTP).

GPS data collection has previously been leveraged to understand and optimize the collection of fecal sludge in Kampala, Uganda [4]. It showed the potential for GPS trackers to be a valuable tool in analyzing fecal sludge management systems. However, the research was within an urban context rather than a refugee camp, and the collection system used trucks as transportation mode rather than manual transport. Furthermore, many research studies have completed site selection of transfer stations using geographic information systems (GIS) and spatial modeling with proximity analysis, however, less have used that method as a first step before optimization modeling [3], [6], [7]. Optimization is a common method in the developed world for site selection, but there is a gap in research conducting mathematical programming for site selection in developing countries [8]. The results of this research act as a proof of concept of methodologies that can be effectively applied in other contexts, including refugee camps and manual transport fecal sludge collection systems.

The goal of this research is to address the lack of access to clean, emptied, and safe latrine facilities within emergency contexts. This requires a fecal sludge management system that is able to provide these services to the entire community. Therefore, the current system service coverage must be analyzed and optimized if necessary. In this research, global navigation satellite system (GNSS) technologies are employed to evaluate and optimize the service coverage of the fecal sludge management system in a refugee camp in Bangladesh.

1.1 Fecal Sludge Management

Sanitation is a crucial field of research due to its impacts on both public health and the environment [9]. The Millennium Development Goals put emphasis on the need to implement improved sanitation systems, such as onsite septic tanks, ventilated improved pit latrines, and centralized sewer-based systems [10]. However, the transport of fecal sludge from these on-site technologies is not included in this definition and has received less attention [10], [11]. On-site sanitation is an affordable fecal sludge management method serving 2.8 billion people globally [4], [12]. Initially considered as a temporary solution, it is now being seen as a long-term alternative to sewer infrastructure in low and middle income countries [10]. The combined capital and operating costs of a sewer-based system is 5 times higher than that of a fecal sludge management system [10]. However, sewers include transport while on-site sanitation requires emptying and transportation by manual service providers and often lacks safe management [4]. In Bangladesh specifically, 40 million new pit latrines were built to help improve access to improved sanitation in rural areas, with the rate of open defecation dropping from 42 % in 2003 to 2 % in 2015 [11], [13]. Unfortunately, this increase in the use of latrines was not accompanied by an increase in safe fecal sludge management practices [11].

Currently, many emptying practices of users and owners are reactive, leading to full latrines and a high risk of exposure to pathogenic organisms [12]. Safe management includes scheduled emptying based on rainfall and tailored to containment size and type, as well as trained manual service providers wearing personal protective equipment [12]. Not wearing personal protective equipment can be fatal to the service providers [12]. Previous research has found that very poorly maintained latrines can lead to residents needing or preferring to open defecate [14], [15]. In Bangladesh, due to poor maintenance, users have even adapted the containment tanks of latrines to ensure that the tanks never require emptying but instead the fecal sludge overflows into an open drain or a local informal sewer contaminating neighboring water sources [12].

Furthermore, it has been found that fecal sludge is often not transported to its end destination but illegally dumped into the surrounding environment [4], [11], [16]. Research in 2011 in Bangladesh found that across three cities, an average of 24.4 % of collected fecal sludge is dumped at an undesignated site where it can contaminate surface water [17]. Research in 2006 in Accra, Ghana found that over 200 000 m^3 of fecal sludge was dumped untreated on a site where it then discharged into the ocean or onto surrounding land [18]. Often, the illegal dumping of sludge is dependent on the income of the residents and whether they can afford official emptying services or if they opt for cheaper alternatives [19]. For example, slum dwellers in Kampala, Uganda, have facilities located in areas with a high water table and therefore fill up fast, however, most dwellers cannot afford to pay for official desludging on such a regular basis [19]. This leads to residents hiring informal manual service providers that dump the fecal sludge into the surrounding environment illegally [19].

When the fecal sludge management system functions as designed, the sludge is transported either to transfer stations for further conveyance at another time or directly to a fecal sludge treatment plant. Transfer stations are storage tanks that allow a fecal sludge management system to optimize its coverage by reducing transportation times of each emptying trip and minimizing associated costs [20], [21]. Transfer stations are usually utilized in order to switch transport mode from manual service providers, which can use narrow paths, to larger motorized vehicles, which can travel longer distances outside of the settlement to the treatment plant and transport larger quantities of sludge at once [20],

[22], [23]. The site selection of these infrastructures can be a challenging decision-making process due to the consequences it can have on the environment and the surrounding residents [20]. Finally, while lots of research has been completed about the utility of transfer stations, very few have actually been installed and even fewer were successful case studies. The flaws linked to transfer stations include the sludge settling and becoming too thick for further transport, improper management, and the “Not In My Back Yard” (NIMBY) phenomenon [24]. This phenomenon refers to the well-known social trend where residents oppose the siting of undesirable facilities near their homes [25]. In Nairobi, disputes over land or management have caused multiple transfer station projects to close or be abandoned, with pit emptiers believing that transfer stations threaten their business [26]. However, transfer stations, such as the successful one set up by Sanergy, are the only way for manual pit emptiers to service more latrines without resorting to dumping sludge at undesignated sites [26], [27].

Finally, Strande et al. (2018) have developed a clear and systemic approach that allows the flows within the fecal sludge management chain to be quantified into six stages: (Q1) total excreta produced, (Q2) fecal sludge production, (Q3) fecal sludge accumulation, (Q4) fecal sludge that is directly dumped into the environment without collection, (Q5) fecal sludge that is collected and dumped into the environment, and (Q6) fecal sludge that is collected and delivered to treatment [28]. In order to understand and optimize a fecal sludge transport system, it is important to understand the flow of fecal sludge within the system. This research specifically analyzes conveyance and therefore the ratio between Q5 and Q6.

1.2 Cox’s Bazar Refugee Camp

The Cox’s Bazar refugee camp is located south of the Bangladeshi town of Cox’s Bazar and close to the border with Myanmar. The camp is split into 34 sub-camps spread around the region and in the district of Cox’s Bazar, with the largest cluster located in Ukhia (Figure 1). The original camp, called Kutupalong, informally began in 1991 in the north-east of Ukhia after thousands of Rohingya fled persecution in Myanmar [29]. Camp 18 is part of the Kutupalong expansion site, which saw extreme growth from August 2017, and is located near the centre of Ukhia [30]. Ukhia is located on a very hilly terrain with a large network of narrow dirt paths (Figure 2) and only a single main road suitable for motorized vehicles following the eastern border of Camp 18. Each camp is separated into Majhee blocks which delineate internal community boundaries. Majhees are community leaders within the refugee population, instated by the Bangladeshi military, and they represent their block politically in camp decisions.

Figure 1: Map showing the location of Camp 18 within Ukhia and within Bangladesh [31]

Figure 2: Camp 18 with its narrow path network and hilly terrain (Photo credit: Christopher Friedrich, April 2019)

Camp 18 has 6540 households with an average household size of 4.6 people [32]. A survey by UNICEF and REACH discovered that 18 % of Camp 18 residents reported having too many people using latrines, 9 % stated that their main experienced problem is that the latrine is full, and 7 % stated the latrine is too far from their household [32]. There are 1172 latrine facilities (each with 1 to 6 latrines) with a total of 1931 latrines in Camp 18, spread over the whole Camp area of 0.75 km2 (Figure 3). Each latrine has a capacity of 2-5 m^3. Camp 18 is one of few camps with a centralized treatment system, with others using up to 30 small-scale decentralized treatment plants per camp [33].

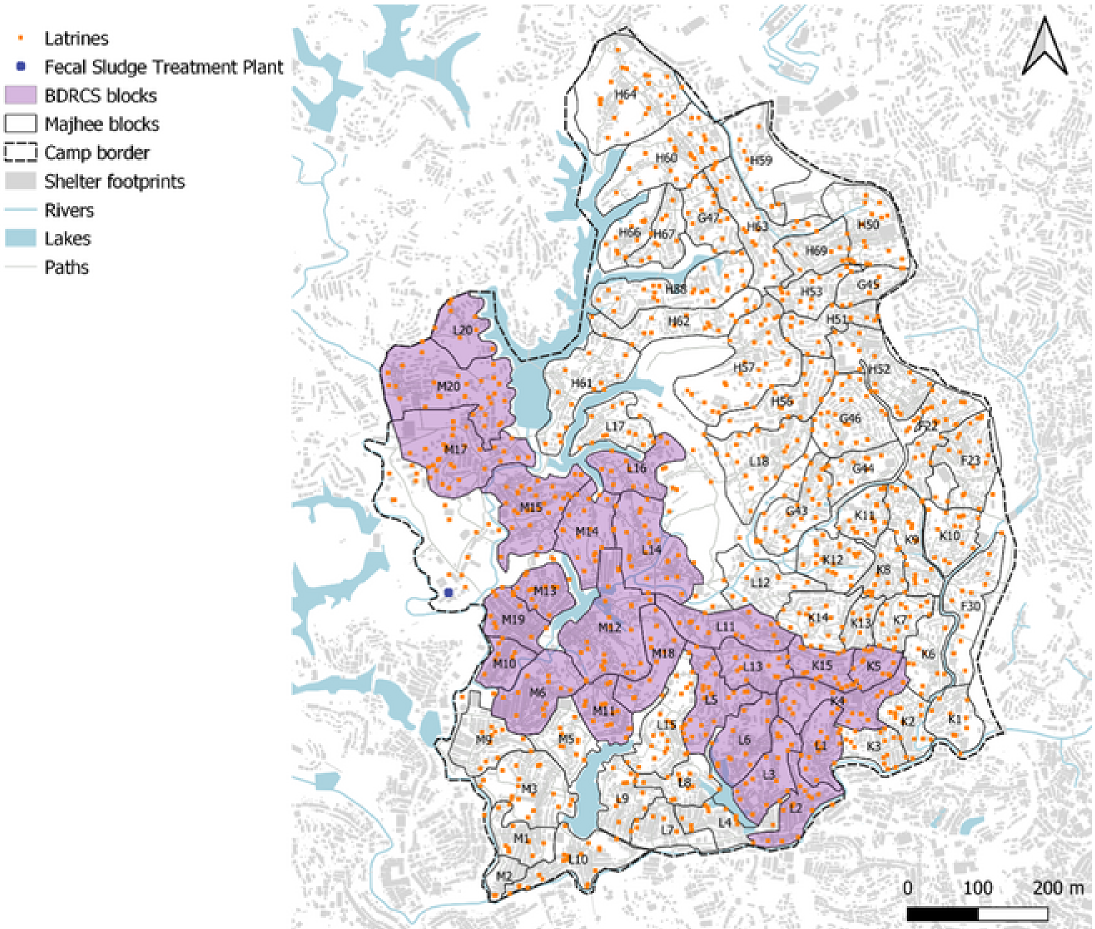


Figure 3: Camp 18 base data overview including FSTP and latrine locations. Majhee blocks that are serviced by the BDRCS desludging team are highlighted. [34]

The Camp 18 fecal sludge treatment plant (FSTP) is based on an anaerobic-aerobic digestion system and the resulting biosolids undergo lime treatment [33]. Due to its centralized nature, the transportation of the fecal sludge to the treatment plant is crucial for an effective management of the system. The hilly topography, dense housing, narrow path network, and monsoon floodings means that the use of motorized transport for collection and transport of sludge within Camp 18 to the camp's sludge treatment plant is not possible. Therefore, manual transportation methods are currently being used. The addition of sludge transfer stations could improve the system by reducing transport times per emptying journey, even though the transport mode cannot be changed.

During the data collection and evolution of this thesis, it was eventually discovered that the BDRCS actually only services part of the latrines within Camp 18, namely the 24 Majhee blocks highlighted in Figure 3. The other 50 blocks of the camp are managed by the German Red Cross or other non-governmental organizations (NGOs). The German Red Cross brings its collected sludge to the BDRCS FSTP, while the other NGOs bring the sludge to some UNHCR FSTPs. Sludge also comes from Camp 19 (managed by the International Federation of Red Cross and Red Crescent Societies (IFRC)) to the BDRCS FSTP. These revelations mean that the service coverage of Camp 18 cannot be certain and neither can the used treatment capacity of the BDRCS FSTP. Therefore, this thesis only analyzes the activities of the BDRCS desludging team working in the 24 highlighted Majhee blocks. An optimization model was then created using the service coverage results to design a potential fecal sludge management system where the BDRCS desludging team and the BDRCS FSTP can successfully service the entirety of Camp 18.

To operate the BDRCS fecal sludge management system, there is a Hygiene Promotion (HP) team and a team for desludging. The HP team is made up of community volunteers and its main responsibility is to sensitize the community on topics concerning sanitation and hygiene. One of their key roles is collecting information on the latrine conditions and conveying any emptying requests to the desludging team. The desludging team is made up of 32 volunteers and two supervisors. This is separated into two teams each with 16 volunteers, of which one volunteer operates the generator, one volunteer operates the pump, two volunteers support the barrel filling, and the remaining 12 volunteers carry the barrels back and forth to the FSTP. Two volunteers carry one barrel between them (see Figure 4) and there are always six barrels being transported while six are being filled up. The desludging team extracts the sludge from the pit using a sewerage submersible pump or mud pump. This pump fill the transportation barrels, which have a capacity of 60 liters but are often filled to only 50 liters to reduce carrying weight and to minimize the risk of overflow. Furthermore, most of the time latrines are fully emptied, but, to keep the latrines functional during heavy rain, the latrines must only be partially emptied.

Figure 4: Example of desludging team activities and tracker placement (Photo credit: Shafiur Rahaman 12/2021)

The Camp 18 FSTP is located on the western border of the camp. On average the BDRCS desludging teams collect 100-120 barrels every day. The maximum treatment capacity of the FSTP is 5 m3/day and on an average day it receives 4 m^3 from various sources. If we say that each barrel is filled with 50 L of sludge and 100 barrels are collected in one day, that would mean that 5 m^3 of sludge is brought to the FSTP. This would imply that only the sludge collected by the BDRCS desludging team uses all the treatment capacity. Therefore, there must be some inaccuracies in the data provided from the field.

The desludging team follows no specific monthly schedule for emptying latrines. The HP team walks around the Majhee blocks and collects desludging requests from residents, which are then formulated into a weekly desludging plan with a priority basis. This considers the size of the pit, the sludge accumulation rate, the type of latrine, and the location of the latrine (when a latrine is in a catchment area it may need to be prioritized due to water logging). Furthermore, every Thursday the desludging team does not collect sludge with barrels but instead with plastic pipes and a pump, servicing two of the closest Majhee blocks to the FSTP, M10 and M19 (see Figure 5).

Figure 5: Piped desludging for blocks M10 and M19 (Photo credit: Shafiur Rahaman, January 2022)

1.3 Spatial Decision Support Systems

1.3.1 Introduction

A geographical information system (GIS) allows for spatial analysis and quantification of the demands and supply of a waste management system, playing a significant role in decision-making for planning and management [35]. Decision support systems (DSS) are tools that can help decision-makers utilize data and models to interpret and solve problems [36]. DSS are particularly useful for solving unstructured problems using analytical techniques and making their solutions easy to interpret for all stakeholders involved as well as flexible to accommodate changes in the environment [36]. Often, data used by decision-makers have a spatial component and GIS technology was developed to organize, analyze and visualize this data [37]. However, GIS does not support the decision-making process in an intuitive, simplified, and result-oriented format for decision-makers, which is where spatial decision support systems (SDSS) originated [37].

SDSS relies on the goals and opinions of decision-makers and stakeholders in order to constrain and interpret spatial data to find a suitable solution to the problem [7]. The criteria used can be conflicting, as well as both qualitative and quantitative, extracted from the priorities of decision-makers and stakeholders. These decisions often relate to spatial planning projects and the methods used are dependent on the size of the problem. With small problems, there are few enough possible solutions that they can be evaluated individually. These are best solved using a cost-benefit analysis when all variables can be expressed with monetary values, or otherwise a multi-criteria analysis. When problems become too large for manual computation and analysis, optimization techniques or simulation techniques, which rely heavily on trial and error, are necessary. While spatial decisions are present in every level of human organization, their implementation only became widespread at the advent of high-speed digital computers due to the computational complexity of these large problems [38]. As this research requires an SDSS that can assess numerous possible transfer station locations, bearing in mind the large number of latrines in operation, an optimization technique was chosen.

GIS is a great first step to satisfy and visualize initial constraints of a siting problem, before entering the results into an SDSS [39]. An SDSS is a simple tool that solves large problems concisely with most previous applications related to efficiently using available resources [40]. Significant amounts of open-source GIS data for Camp 18 have been made available through humanitarian aid data sharing platforms, and within this research, further primary data was collected to better understand the management of the system and the movement of the fecal sludge from the latrines to the FSTP. With this data and due to the large research area of Camp 18, a mixed-integer optimization model was then used to optimally locate sludge transfer stations [35]. This model was solved using a commercial optimizer (XPRESS-MP). These transfer stations should simplify the task of the desludging teams by shortening the distance per sludge transport journey.

Finally, NIMBY will be referred to often within this thesis as it is a major limiting factor of the methodology. This research lacks feedback and insights from the residents and stakeholders of the community, which is fundamental for site selection in any successful infrastructure project. Only spatial features are used within the GIS modeling to select potential transfer station sites which are inserted into the optimization model (See Section 3.2.5). However, if these methodologies were recreated, a co-creation session with stakeholders could resolve this NIMBY limitation by altering the set of potential sites used by the model.

1.3.2 Optimization Models

There have been numerous studies using optimization methods for waste management facility site selection. Chen et al. (2021) defined three objectives as key to waste transfer site selection when highlighting the issue of NIMBY in rural areas: maximize distance between transfer site and settlement; minimize total cost of transportation; minimize necessary construction costs [25]. Yurteri and Siber (1985) designed their linear transportation model to minimize the transportation costs between demand centers and transfer stations [41]. They found that adding transfer stations to this solid waste truck-based collection system in Ankara had around a 20 % reduction in total transportation costs.

Jabbarzadeh et al. (2016) created a multi-objective linear programming model aiming to optimize the number, location and type of transfer station [42]. Due to its multi-objective nature, a weighting method was utilized to prioritize the objectives and a fuzzy approach was employed to find effective solutions. Shi et al. (2019) not only minimized cost for siting a construction waste recycling plant, but also negative environmental effects, in their multi-objective optimization model solved using a genetic algorithm [43]. The literature review of Habibi et al. (2017) found that all the models they examined defined the objective as a minimization of the total cost [44]. Therefore, they designed a multi-objective model that minimizes total cost and minimizes maximum cost. Chatzouridis and Komilis (2012) developed a 4-step methodology including: exclusion of unsuitable areas; applying a siting approach within these areas based on proximity to municipality centers or in critical locations to serve multiple municipalities; developing an objective function minimizing total solid waste collection costs; and finally developing the optimization model in a user-friendly Excel spreadsheet [45].

In the work of Eiselt and Marianov (2015), optimization was used as an early step in the methodology to define a cost-minimizing solution [39]. These facility locations were then used as center points of neighborhoods of a predefined size, which underwent spatial overlays of criteria to specify down to a remaining set of suitable areas. Asefi et al. (2015) used a mixed-integer programming model to not only determine the optimal transfer station locations but also the routes taken to transport the waste to the transfer stations, forming a location-routing problem [46]. Erkut et al. (2006) developed a mixed-integer linear programming model with multiple economic and environmental objectives [47]. Such a method cannot simultaneously optimize all objectives, therefore a Pareto optimal solution is found, which cannot be improved with respect to all objectives simultaneously. Coutinho-Rodrigues et al. (2012) developed a mixed-integer linear programming model with the objectives of minimizing total investment costs and minimizing total dissatisfaction [48]. The model is used to determine the number of facilities to be constructed, their locations, and their capacities.

As demonstrated in this literature overview, there are multiple types of optimization models and overall approaches to optimization problems. The first distinction that can be made is whether the decision variable is discrete or continuous. Having a whole area in which to locate a potential site is a continuous problem with a continuous solution space, where every point in the plane is a feasible location to locate facilities [49]. Having a selection of potential sites makes the decision variable discrete and the problem more manageable.

There are 8 different types of basic facility location models with set covering, maximal covering, p-center, and p-dispersion based on a maximum distance objective and p-median, fixed charge, and maxisum based on a total or average distance objective [38]. These all require the underlying network, the demand centers, and the existing facilities as input data before optimizing for some distance-related objective [38]. The set covering location model determines the minimum number of facilities necessary to meet the entire demand [38]. The maximum covering location model sets the maximum number of facilities that can be built and determines the total possible demand [38]. The p-center model minimizes the maximum distance the demand is from its closest facility and the number of facilities is predetermined [38], [50], [51]. The p-dispersion model is opposite to the p-center model. It only considers the distance between the facilities and ignores the distance between the facilities and the centers, with its objective being to maximize the minimum distance between any two facilities [38]. The p-median model minimizes the demand-weighted total distance between the demand centers and the facilities, but also assumes the number of facilities to be placed is known and that the facilities have no capacity limits [38]. The fixed charge location model aims to minimize both facility and transportation costs. However, due to facility capacities, demand may not be assigned to its closest facility [38]. Finally, the maxisum location model maximizes the distance between the latrines and the transfer facilities.

1.3.3 Optimization Solvers

Spatial optimization problems can contain multiple objectives and conflicting constraints, that make them too complex to be solved without computational programming [52]. However, the computational power needed to solve such models means that certain compromises have to be made to favor either speed, precision, or complexity. Therefore, methods have been developed that include one compromise. General methods are exact and simple to apply but often slow to compute. Specialized methods are exact and fast to compute but very difficult to understand and apply. Finally, heuristic models are fast to apply and easy to understand but will only obtain an approximate solution.

Having chosen the factor to compromise, the next decision step is made based on the type of optimization model necessary, including discrete or continuous with linear or non-linear objective and constraint functions. These criteria help determine the best solver to use.

Finally, solvers can also be categorized into open-source or commercial, based on their licensing. The most advanced of all solvers are the commercial solvers CPLEX, XPRESS, and GuRoBi [52]. In the comparative analysis by Anand et al. (2017), the performance of these 3 solvers were evaluated. They found that no solver is best across all problem types, with CPLEX and GuRoBi excelling on real life problems, while XPRESS performs best on complex and highly scalable problems due to its multithreading capabilities [52].

2 Research Questions

2.1 Research Gaps

The previous literature review provides the basis for which the research gaps are identified. Firstly, the sludge management research field is lacking information on the service coverage of a manual transport-based sludge emptying service as well as on the spatial capacity of a sludge management system within a refugee camp [4]. The more common sludge transport mode is by truck or a combined network of manual service providers, transfer stations, and trucks. However, due to the unique conditions in the Cox's Bazar refugee camp, there is no large road access to the fecal sludge treatment plant in Camp 18. Therefore, it is important to understand what the service coverage of such a unique system is for future planning and decision processes.

Various factors can influence the spatial and temporal distribution of sludge emptying events. The temporal distribution can be influenced by population density and income levels [9]. Some possible temporal factors mentioned by Schoebitz et al. (2017) include "monthly precipitation (e.g., containment technologies fill up faster), increased income during crop harvest periods (e.g., increased income), and timing of school fees and public holidays (e.g., decreasing emptying service requests due to extra expenditures)" [4]. Most research on this topic explores contexts where the residents pay for their own emptying services, rather than latrines being publicly maintained facilities. Therefore, there is a knowledge gap regarding the spatial and temporal distribution of sludge emptying events in public sludge management systems. The desludging teams are in charge of controlling this distribution with data collection and prioritization planning based on resident requests, sludge accumulation rate, and latrine type. However, nothing is known about the efficacy of this planning process on obtaining an equitable distribution of sludge management services. Therefore, it is important to understand what the spatial and temporal distribution of a publicly managed sludge emptying service is and what are its largest influencers.

Finally, many research projects in the field have confirmed that fecal sludge is often dumped in the surrounding environment rather than being transported to a treatment facility [4]. Literature particularly highlights this practice among manual emptying services, as they are often run as an informal alternative to official truck-based emptying [19]. There seems to be a lack of research addressing to what extent the practice of illegally dumping sludge is also common among publicly managed manual sludge transporters.

Therefore, the three key knowledge gaps explored further within this research consist of:
- What is the service coverage of a manual transport-based sludge emptying service?
- What factors influence the spatial and temporal distribution of sludge emptying events?
- Does organized manual emptying follow the illegal dumping statistics?

2.2 Research Questions

Based on the identified research gaps, several research questions were formulated and divided into two stages of this research. These stages are written as overarching research questions with sub-questions. The overall research question for the thesis is:

To what extent can GNSS data collection and spatial decision support systems be leveraged to optimize fecal sludge transport in Camp 18 of the Cox's Bazar Refugee Camp?

2.2.1 What is the current service coverage of the camp 18 fecal sludge treatment plant?

The research questions within this stage of the research are:

1. What is the spatial and temporal pattern of the latrine emptying process?
2. What proportion of emptying processes include dumping sludge at an undesignated site?
3. What is the maximum distance and elevation change of the transportation routes at which efficiency is impacted negatively?

The following hypotheses were created to match these research questions:

1. Areas closest to the FSTP are serviced more frequently than areas with higher population densities
2. 20 % of journeys are unaccounted for and correspond to inaccurate logging and fecal sludge dumping in an undesignated site (rounded from the average amount of collected fecal sludge in Bangladesh that is dumped in an undesignated site)[17]
3. A trend of fatigue can be observed in the velocity data of the transportation routes that hint at a maximum transportation distance and elevation change for manual emptying service providers

2.2.2 How can the current fecal sludge transportation system be optimized?

The second stage of the research has the following research questions:

1. Does the system require a new FSTP or transfer stations to meet demand?
2. What locations are optimal for transfer stations, considering environmental, social, and transportation constraints?
3. What is the optimal number of transfer stations?

As this stage of the research is more analytical, based on the data collection, no hypotheses were deemed necessary as they would be highly approximative and not sufficiently context based.

3 Methodology

3.1 Barrel Tracking

3.1.1 Introduction

This research depends on obtaining high-quality data in order to gain an understanding of the service coverage of the Camp 18 FSTP and the limitations of the management system. This type of data is not within the large amounts of open-source data available for the Cox's Bazar refugee camp, which focuses on surveys or static coordinates of points of interest. Therefore, a large portion of this research involved conducting primary data collection with the BDRCS desludging team, who were crucial partners. The goal was to use a global navigation satellite system (GNSS) device to track the movements of the transportation barrels within the fecal sludge management system. This provides key information on the movement of sludge from latrines in Camp 18 to the BDRCS FSTP, and any limitations with this transportation system may be deduced from the collected data.

3.1.2 Sensor Selection

Many asset management GPS trackers exist that would seem to meet the needs of this research. However, due to the extreme environment in which the trackers must work, there were many limitations that had to be circumvented.

First of all, the ideal tracker would have a live-tracking feature directly visualizing the data on an online platform accessible by researchers anywhere in the world. However, such live-tracking technologies require sim cards and a mobile phone network, Wi-Fi, or other connected devices that could create a mesh network. None of these are available in the Cox's Bazar refugee camp, mainly due to regulations enforced by the Bangladeshi government. Therefore, log-based GPS trackers were used, which must be collected from the field weekly to manually download the data. The most vital feature of the tracker was its position accuracy and logging frequency, since the goal was to identify the paths on which the barrels of sludge are transported and the velocity of transport. Unfortunately, this feature has a large influence on battery life and while many waste management tracking devices can rely on a direct power source from the transportation vehicle, this is not possible with manual transport solutions. Therefore, the aim was simply to minimize the frequency so that charging the devices was not necessary, to maximize the time spent by the devices within the collection system.

Having explored a wide range of options in the GPS tracker market to find a device that met these requirements, the final device chosen for this research was the P-10 Pro from the German company Columbus. The P-10 Pro obtains an extremely high position accuracy of less than 1 meter by processing two different band-frequency global navigation satellite system (GNSS) signals, eliminating ionospheric influences and signal reflections [53]. The GNSS multi-constellation positioning system results in more rapid and effective positioning capabilities worldwide than the normal single-constellation GPS positioning system [53]. This position data can be logged at a frequency of 1 Hz (1 waypoint every second) for a duration of 50 hours. Finally, the small size of the P-10 Pro and its IP66 rated durable casing ensures the device's longevity in these extreme conditions.

3.1.3 Tracking

These data loggers were subsequently bought and transported to Bangladesh. Due to various complications with shipping and customs, only 20 data loggers were used for this research. Half of the trackers were in the field from November 27th 2021 till January 30th 2022, while the other half only arrived in the field on December 11th 2021. Therefore, while the entire research study lasted ten weeks, two of these weeks were only recorded by ten trackers. The trackers were attached to the sludge transport barrels and configured to record at a frequency of 1 Hz. Due to their battery-saving sleep mode, they only record the barrels when they are moving. Therefore, the trackers were only removed from the barrels every two days for charging and data downloading. Figure 4 shows the placement of the tracking device on the barrels and gives an example of how the barrels are carried.

3.1.4 Interviews

Due to the limited infrastructure in the developing world, researchers have often found interviews to be the best available means of data collection [14]. In order to build an understanding of the context of this research, email correspondence with BDRCS management within Camp 18 was carried out. This primary data collection substantiated all the information provided in the introduction of this thesis.

Primary data collection was also carried out in the field, through interviews between the research assistant Shafiur Rahaman, the desludging team supervisors, and volunteers. It was important to cross-check the GNSS data with the weekly desludging plans of the desludging team obtained through the interviews. As GNSS loggers were placed on 20 barrels out of the 24 used on a daily basis, the plans were important to fill any data gaps from the data collection. Two separate planning schedules were provided by the desludging team and the BDRCS management. When compared, these schedules have discrepancies with each other as well as with the tracking data. Therefore, some of the Majhee blocks seem to have been serviced the day before or after it was noted. For this research, only the desludging plans produced by the desludging team were used, to avoid too many contradicting data sources. Unfortunately, due to a delay in the field collection, neither desludging plans were available for the month of November, which accounts for four days within the study period. Therefore, the results extracted from the desludging plans must be taken as an underestimation for the ten weeks of study.

Furthermore, to better understand the tracker data, the following questions were asked to the desludging team that might help understand certain choices:

1. What is your limiting factor when collecting sludge (what might be preventing them from serving all the latrines, or serving certain latrines more frequently)? For example: fatigue-related effects from distance, elevation change or weight; or politics; or infrastructure maintenance; etc.
2. What blocks do you find most difficult to service?
3. What could be the reason why a latrine was not serviced in the research period?

This helped develop an understanding of the influencing factors on the spatial and temporal pattern of the desludging activities.

3.1.5 Data Processing

The data loggers produce a comma-separated values (CSV) file for every continuous track recorded between sleeping instances. This CSV file has a data point for every second of tracking with columns for: date, time, latitude, longitude, altitude, speed, and device angle.

A python script was developed to parse this data into useful and usable information. Stops were defined as instances when the tracker remained in the same radius of 15 meters for a period of 3 minutes. If a stop was found, then this stop needed to be classified as either “FSTP”, “stop_pre_latrine”, “latrine”, or “stop_post_latrine”. The conditions for each classification are as follows:

- FSTP: Stop within 40 meters of the FSTP coordinates
- Stop_pre_latrine: Stop after the FSTP and before a latrine
- Latrine: If any two stops are in a radius of 15 meters of each other, the assumption is made that both of these stops were at a latrine and the latter stop is classified as “latrine”
- Stop_post_latrine: Stop after a latrine and not close to the FSTP

This data was used to determine the spatial and temporal pattern of the fecal sludge management system. Specifically:

- The percentage of latrines in the planned zone that were emptied
- The frequency at which a latrine was emptied
- The percentage of stops that take place after a latrine

To determine the number of latrines serviced, it was assumed that if any of the stops classified as “latrine” were within 10 meters of a known latrine, then that latrine was serviced. The data collected follows the natural behavior of humans rather than a machine. Therefore, the parsing methodology is not perfect and may not detect the stop type in every desludging case. Some latrines may have been missed if they were visited for shorter than the 3-minute interval required to have two stops close together. However, as most latrines are visited by more than one barrel in order to be successfully emptied, it is assumed that all latrines were accurately recorded. This proximity repetition methodology reduces the likelihood of false positives, and the nature of the data, with multiple visits to one latrine, reduces the likelihood of false negatives. Finally, due to unplanned stops by the desludging teams or incorrect latrine coordinates, this method is not perfect, but the results are a good approximation of the total number of serviced latrines. Moreover, interviews with the desludging team will help verify these results and highlight the potential spatial and temporal influencers of their work, such as distance, population density, elevation change, politics, etc.

The open-source GIS software QGIS was used to spatially analyze the collected data. The vector point data was processed into vector line data to visualize the routes. An analysis was completed to see the percentage of routes where the shortest path using the network was not the one used. Such routing behavior could be caused by the desludging team choosing to deviate around hills rather than scale them as well as traveling through dried-up lakes outside of the monsoon season. The limitation of this analysis was the open-source path network data available, which does not perfectly match with the actual paths used by the desludging team. Therefore, the calculated shortest path network analysis by QGIS from the serviced latrines to the FSTP sometimes used a detour that was unnecessary in reality. The collected data also enables the analysis of preferred routes by counting the number of journeys that pass specific points on the path network. Initially, this information was to be used in the optimization model to prioritize transfer sites located on commonly used paths. However, this was not possible with tracker data for only a subsection of the camp. The analysis was left in the thesis as it is believed that the results can also be interesting for further path improvement projects within Camp 18.

Finally, the python script attempts to identify fatigue thresholds of the desludging teams when they are carrying full barrels back to the FSTP. It records the average velocity of the desludging team after leaving the latrine as well as the distance traveled and the elevation change to see if there are any correlations. After a graphical assessment, a simple Multiple Linear Regression Model and ANOVA test was carried out to see how each variable individually affects the average velocity.

3.2 Optimization

This research focuses on the strategic planning of site selection rather than route optimization. Route optimization is a tactical practice, which is flexible and requires more complex management, while site selection is permanent, aiming to simplify the management system [54].

In order to make the optimization problem a more manageable size, a discrete model was designed with predetermined potential sites rather than a continuous solution space [49]. When selecting the optimal sites for the placement of a second sludge treatment plant and sludge transfer stations, it is important to consider the social and environmental consequences of such a decision (see Section 3.2.5). Therefore, GIS followed by the commercial optimizer XPRESS-MP were used to combine a wide range of spatial queries to optimize the site selection.

Several basic facility location models were considered before selecting the p-median model as the most appropriate methodology for this context. The p-median model minimizes the total distance traveled in the system rather than the maximum distance traveled in one trip. This is beneficial as it prevents the model from being too restrictive and it reduces computation time [55]. Furthermore, with the distance minimized, the p-median model assigns demand to the closest facility, unlike the fixed charge and maxisum models. All these characteristics make the p-median model most suitable for this research. Another objective is for the model to be able to determine the number of facilities needed. Therefore, the set covering location model remains a suitable addition to the p-median model as it determines the minimum number of facilities needed for the system demand to be met. Therefore, the final model designed for this research begins with set covering, to determine the necessary number of facilities. Then a p-median model is implemented to select optimal locations for these facilities in order to minimize the total weighted distance required to move the sludge (the weight) within the system.

It is important to note that the desludging teams should not be forced to always rely on the transfer stations when the FSTP is at a similar distance. Therefore, the FSTP also counts as a transfer facility, and it has an infinite capacity. This means that with models such as set covering, the FSTP could satisfy all the demand and the minimum number of additional transfer facilities necessary would be 0. Due to this classification of the FSTP as a facility, another constraint must be added to the model to ensure that minimizing the total distance of the system does not result in bypassing the use of any transfer facilities. The constraint chosen was the addition of a maximum distance between every latrine and the allocated transfer site.

Two different optimization models were designed, with and without the consideration of elevation. The largest load of sludge will be transported from the transfer stations to the FSTP. Therefore, the second model minimizes the change in weighted elevation between the transfer site and the FSTP as well as minimizing the total weighted distance of the system.

In order to design a model which minimizes both distance and elevation change, the importance of each variable needs to be quantified so that the result represents the accurate influence ratio. An influence ratio must also be determined for elevation gain and elevation loss in order to calculate an appropriate weighted elevation change value. This assessment is carried out on the service coverage results in Section 4.1.2. The assessment results are then inserted in the model as weighting factors $\boldsymbol{a}$ and $\boldsymbol{b}$ for elevation gain and elevation loss, and weighting factors $\boldsymbol{A}$ and $\boldsymbol{B}$ for elevation change and distance. In the following outline of the optimization model, the addition of elevation is highlighted in orange.

3.2.1 Notation

3.2.1.1 Sets

J: set of latrines where sludge is assumed to be concentrated
K: set of sites where transfer facilities may be located, including FSTP as k = 0

3.2.1.2 Decision Variables

Location y_k = 1 if a transfer facility is (to be) located at site k; otherwise y_k = 0
Capacity z_k: capacity of the transfer facility located at site k
Allocation x_{jk}: sludge from latrine j is allocated to a transfer facility that will exist, located at site k

3.2.1.2 Parameters

d_{jk}: distance between latrine j and site k
d_{k0}: distance between site k and site k = 0 which is the FSTP
g_{k0}: elevation gain between site k and site k = 0 which is the FSTP
l_{k0} : elevation loss between site k and site k = 0 which is the FSTP
u_j : sludge from latrine j (volume of sludge produced)
z_{mink} / z_{maxk}: minimum (maximum) capacity of a facility located at site k
r_{jk} = 1 if site k is acceptable distance from center j, otherwise r_{jk} = 0

3.2.2 Objective Function

$$\min Y = \sum_{k \in \boldsymbol{K}} y_k \qquad \textit{Minimization of number of transfer facilities}$$

$$\min D = \sum_{j \in \boldsymbol{J}} \sum_{k \in \boldsymbol{K}} d_{jk} x_{jk} + \sum_{k \in \boldsymbol{K}} d_{k0} z_k \qquad \textit{Minimization of weighted distance}$$

$$\min C = \boldsymbol{A}\left(\sum_{j \in \boldsymbol{J}} \sum_{k \in \boldsymbol{K}} d_{jk} x_{jk} + \sum_{k \in \boldsymbol{K}} d_{k0} z_k\right) + \boldsymbol{B}\left(\boldsymbol{a} \sum_{k \in \boldsymbol{K}} g_{k0} z_k + \boldsymbol{b} \sum_{k \in \boldsymbol{K}} l_{k0} z_k\right) \qquad \textit{Minimization of cost}$$

3.2.3 Constraints

$$y_0 = 1 \qquad \textit{FSTP is always seleted as a site}$$

$$\sum_{k \in \boldsymbol{K}} x_{jk} = u_j, \forall j \in \boldsymbol{J} \qquad \textit{Sludge collection demand is satisfied}$$

$$x_{jk} \leq u_j r_{jk} y_k, \forall j \in \boldsymbol{J}, k \in \boldsymbol{K} \qquad \textit{Sludge is allocated to sites where } \text{transfer } \textit{facilities (will) exist}$$

$$z_k = \sum_{j \in \boldsymbol{J}} x_{jk}, \forall k \in \boldsymbol{K} \qquad \textit{Capacity } \text{of transfer facilities } \textit{can accomodate sludge}$$

$$z_{mink} y_k \leq z_k \, , \forall k \in \boldsymbol{K} \quad Capacity\ of\ facilities\ is\ above\ minimum$$

$$z_k \leq z_{maxk} y_k \, , \forall k \in \boldsymbol{K} \quad Capacity\ of\ facilities\ is\ below\ maximum$$

3.2.4 Solver

As a discrete solution space was chosen based on geographical limitations for site selection (as explained in Section 3.2.5), and the objective and constraint functions are linear, a mixed-integer linear problem is defined. In this research, the compromise was made on computational time while upholding the precision and comprehensibility of the results. Therefore, a general method was chosen that is suitable for mixed-integer linear models. In the end, the model size was small enough that the computation time was only seconds. A mixed-integer linear model is tackled with general methods including Branch-and-bound, Cutting planes, and Branch-and-cut, and can be solved with the commercial solvers CPLEX or XPRESS.

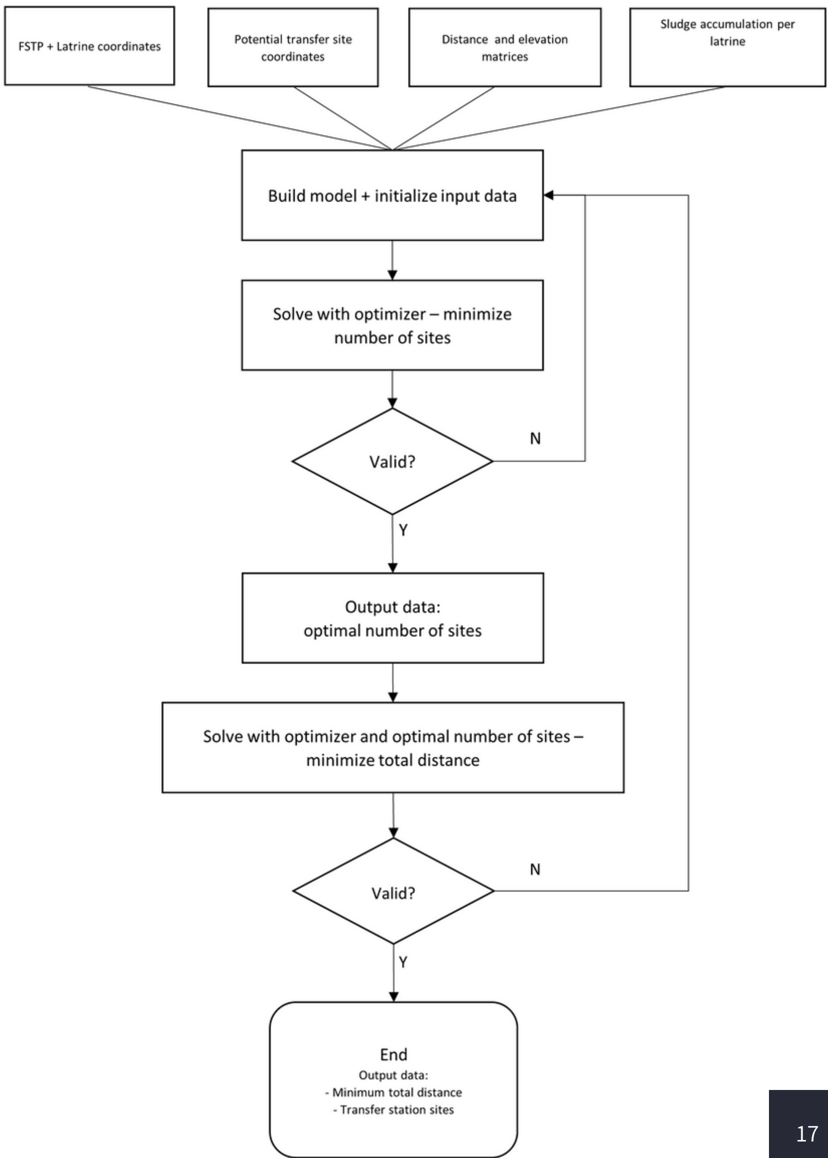
Mixed-integer linear problems have only become practical modeling structures in the last 20 years due to the improvements in commercial solvers [56]. Due to their complexity, the same problem 35 years ago would take years to solve while now it would only take seconds [56]. For this research the well-known commercial solver XPRESS was chosen due to its excelling performance on complex problems [52].
A flow chart demonstrating the steps of this optimization process can be found in Figure 6.

3.2.5 GIS Analysis

The optimization model was initially built with a small randomized dataset to reduce processing power needs. The input data was prepared separately and added once the model was functioning as intended. The data required by the model included coordinates for the FSTP and the latrines, coordinates for the potential transfer station sites, a distance matrix between the latrines and the transfer sites, a distance matrix between the sites and the FSTP, an elevation matrix between the sites and the FSTP, and the sludge accumulation per latrine (Figure 6). Most of this data was extracted from QGIS after existing open-source data was manipulated with various GIS tools.

The distance matrices were created using a QGIS tool called QNEAT3 OD Matrices and the path network data available on humanitarian aid data

Figure 6: Optimization model flow chart



sharing platforms. It provides the network-based distances between the FSTP, the latrines, and the potential transfer site locations. Due to some missing links in the path network, it had to be manually patched and spokes were added to connect the path to every object within the system. The elevation matrix creation process was more complicated as there were no existing tools within QGIS to create this matrix. A network analysis was used to find the shortest path between every potential transfer site and the FSTP. Points were set every 5 meters along these paths and an altitude was associated to each point using a digital elevation model. Then a PyQGIS script was written to analyze these points and determine the elevation gain and loss along each path.

The sludge accumulation rates for each latrine were calculated using certain assumptions. Firstly, the widely accepted value for sludge accumulation rate for the Cox's Bazar refugee camp is 0.5 liters/person/day [33]. Then, multiple steps were necessary to determine the number of people using each latrine. It was assumed that every distinct shelter within the camp is inhabited by 1 household. The average household size in Camp 18 is 4.6 people [32]. Then, using the QGIS tool "distance to nearest hub", an assignment was made between each shelter and its closest latrine. As latrines are not always placed close to the path network, large detours were observed when initially computing the allocations using the path network. Therefore, it was assumed that most residents will walk to their closest latrine in a straight line, irrespective of the path network (Figure 7). Finally, a table was created stating the number of shelters allocated to each latrine, which can then determine the sludge accumulation rate (L/d) for each latrine. Some latrines were assigned no users in the allocation process, therefore a sludge accumulation rate of 1 L/d was set for these latrines as every latrine is assumed to be used to some degree.

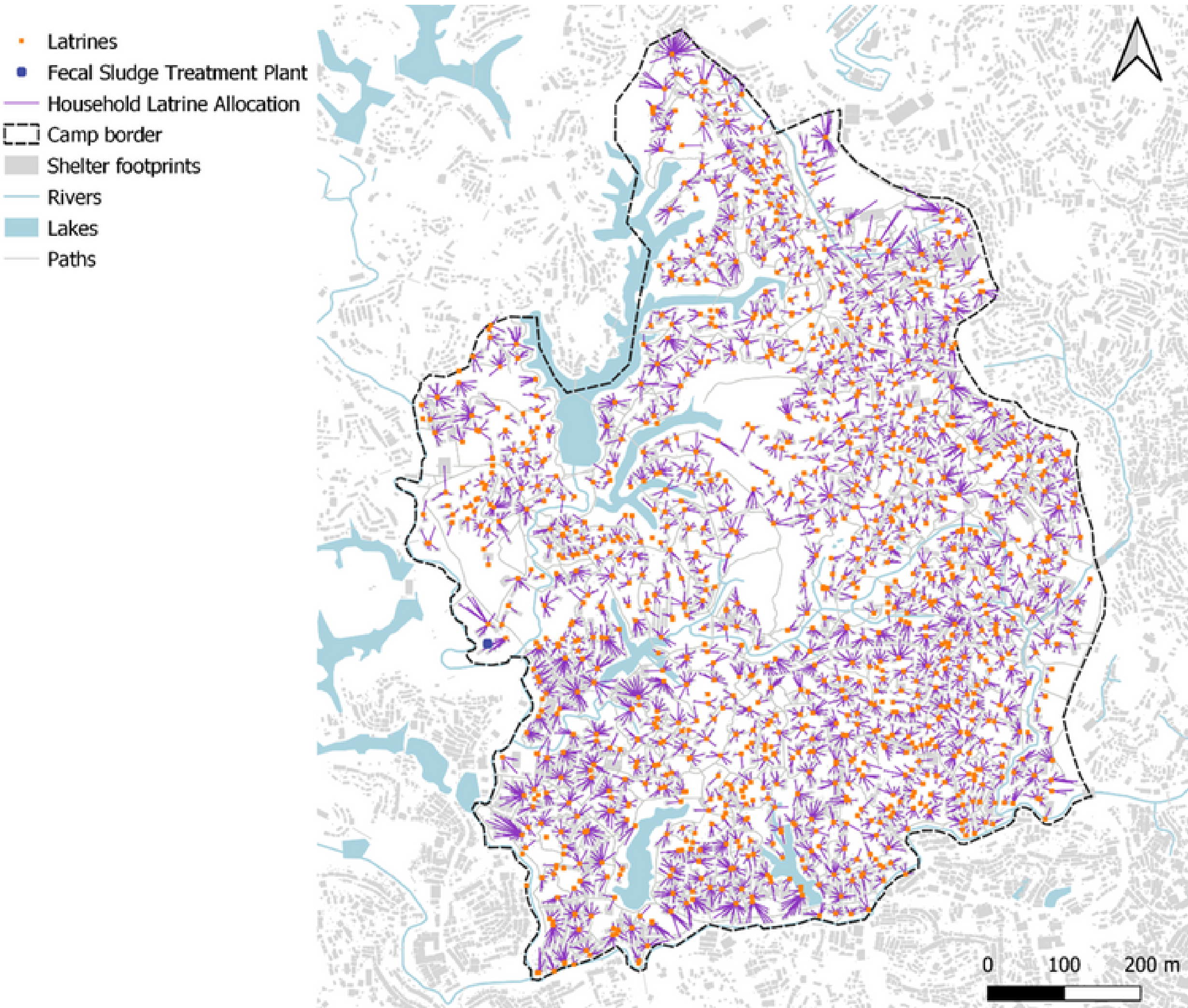


Figure 7: Allocation of nearest latrine to a shelter for sludge accumulation rate estimations [57]

The potential transfer station sites were selected using multiple base criteria and constraints; however, the final result can never be as accurate as having completed a co-creation session with residents to obtain a socially acceptable set of sites. This would prevent the phenomena of NIMBY from playing a role in the social acceptance of the new transfer stations. Due to COVID-19 and the online constraints in place at the time of this thesis, only GIS data was used for the site selection. This limitation is mentioned further in the Discussion section. The initial criteria for the placement of a transfer station are that it is within 1 and 10 meters of the main path network to ensure good accessibility while not being located on a path. Then the following constraints (as areas to avoid) were applied to the initial potential zones:

- Flood zones (Figure 9)
- Nature areas
- Slopes steeper than 13 degrees (the lowest equal count quantile of all elevations) (Figure 10)
- Lakes and rivers, with a buffer of 5 meters
- Buildings, with a buffer of 10 meters
- 100-meter buffer around the FSTP
- The army road on the eastern border of the camp, with a buffer of 10 meters

The final sites selected needed to be at least 4 m^2 and if multiple options were located in close proximity, the most central site was selected. A diagram of this suitability analysis is shown in Figure 8 as well as some of the applied spatial constraints in Figure 9 and Figure 10.

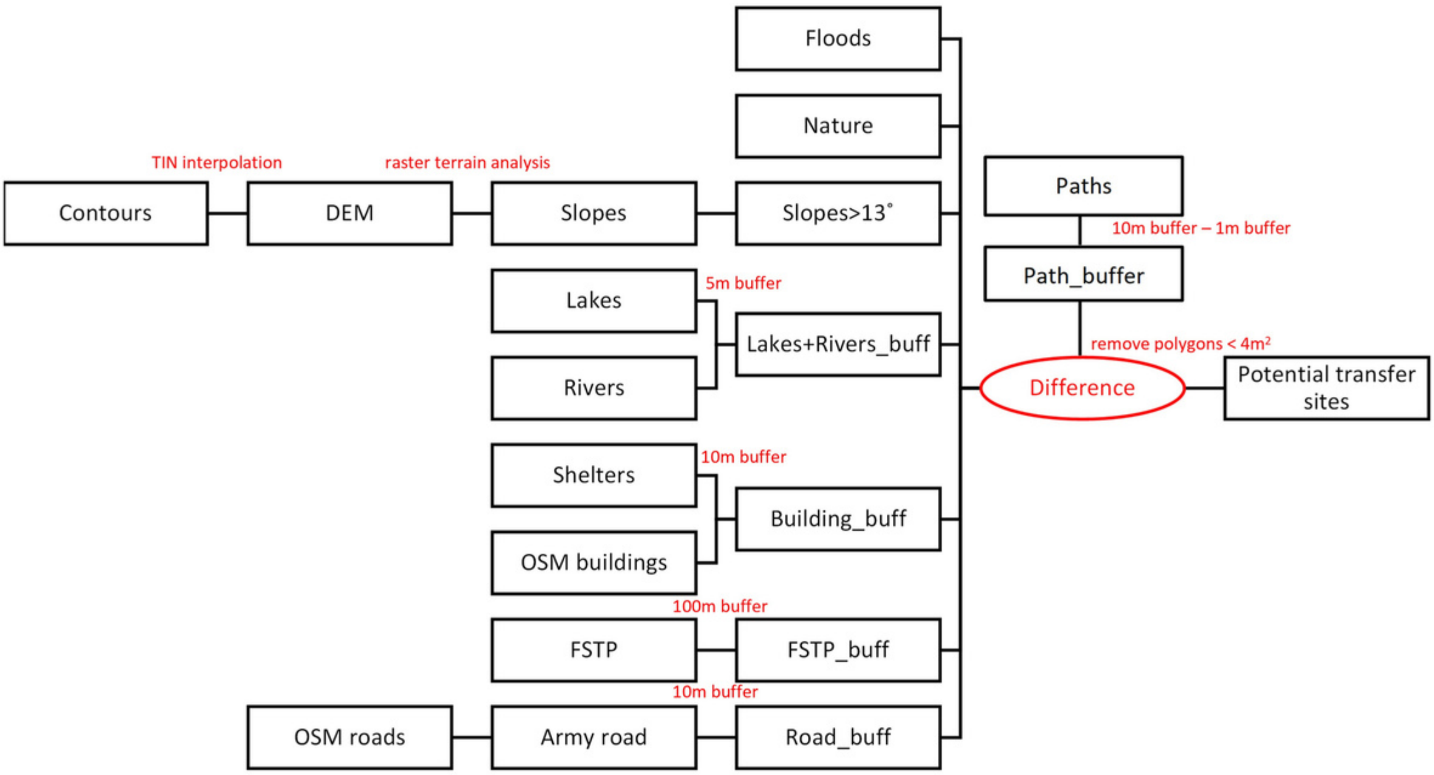


Figure 8: Suitability analysis process chart

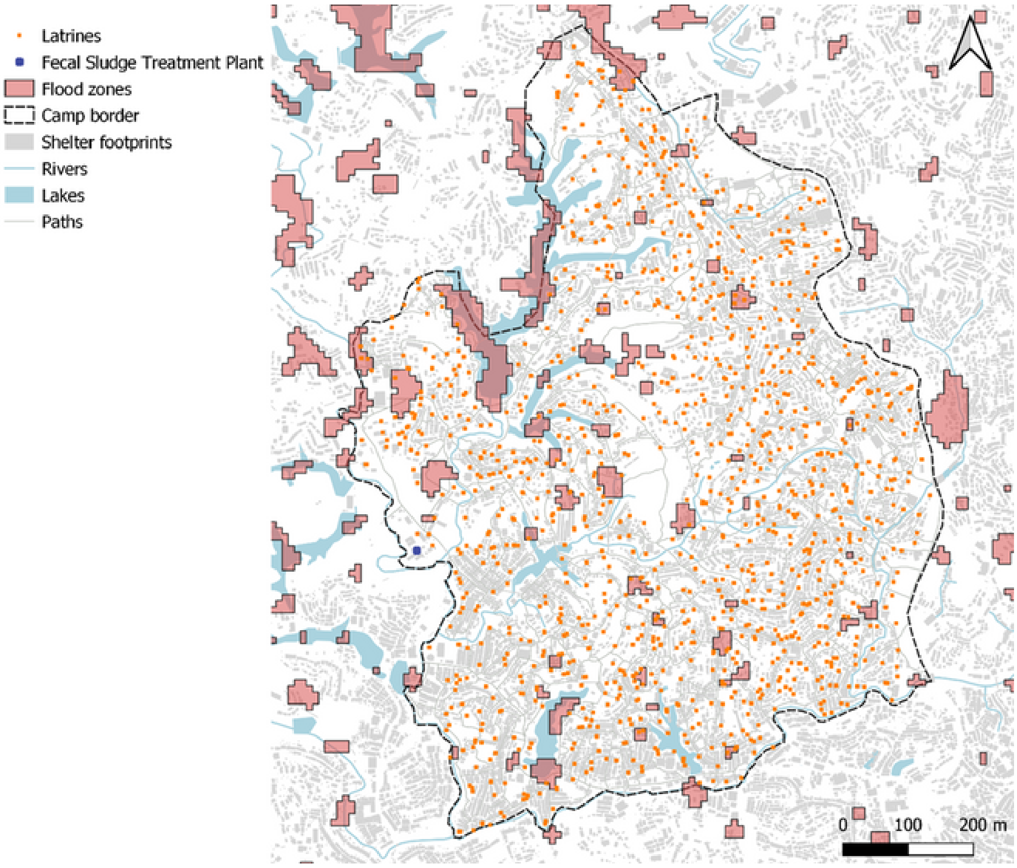


Figure 9: Map depicting flood zones [58]

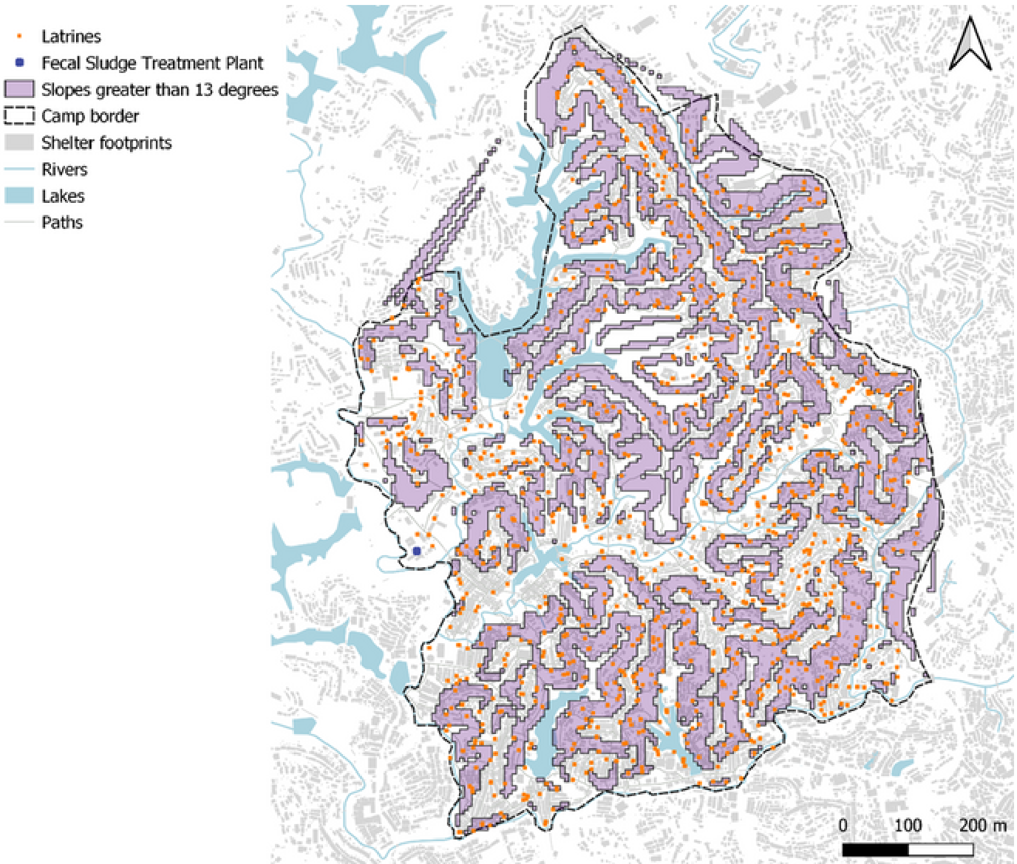


Figure 10: Maps depicting slopes greater than 13 degrees [59]

The above assessment was performed a second time to determine whether there are any potential sites for a second FSTP. The methodology was only altered to include the whole area, rather than areas close to the path network. The paths were buffered with 2 meters and then removed from the potential sites.

4 Results

4.1 Service Coverage

4.1.1 Spatial and Temporal Pattern

The service coverage assessment was carried out only considering the BDRCS managed Majhee blocks of Camp 18. This is approximately 20 % of the whole camp area, 24 of the 74 Majhee blocks, and contains 379 of the 1172 latrine facilities present in Camp 18. The GNSS data loggers show that 1 of these 24 blocks was not serviced, namely M11. However, servicing a block does not mean all the latrines within that block were serviced. Within the ten weeks of study, the BDRCS desludging team serviced 186 latrine facilities, which is 49 % of all latrines in the BDRCS service area (Figure 11). As each facility has 1 to 6 latrines, overall 325 latrines were serviced out of the 651 in the BDRCS area or the 1931 latrines in the whole camp.

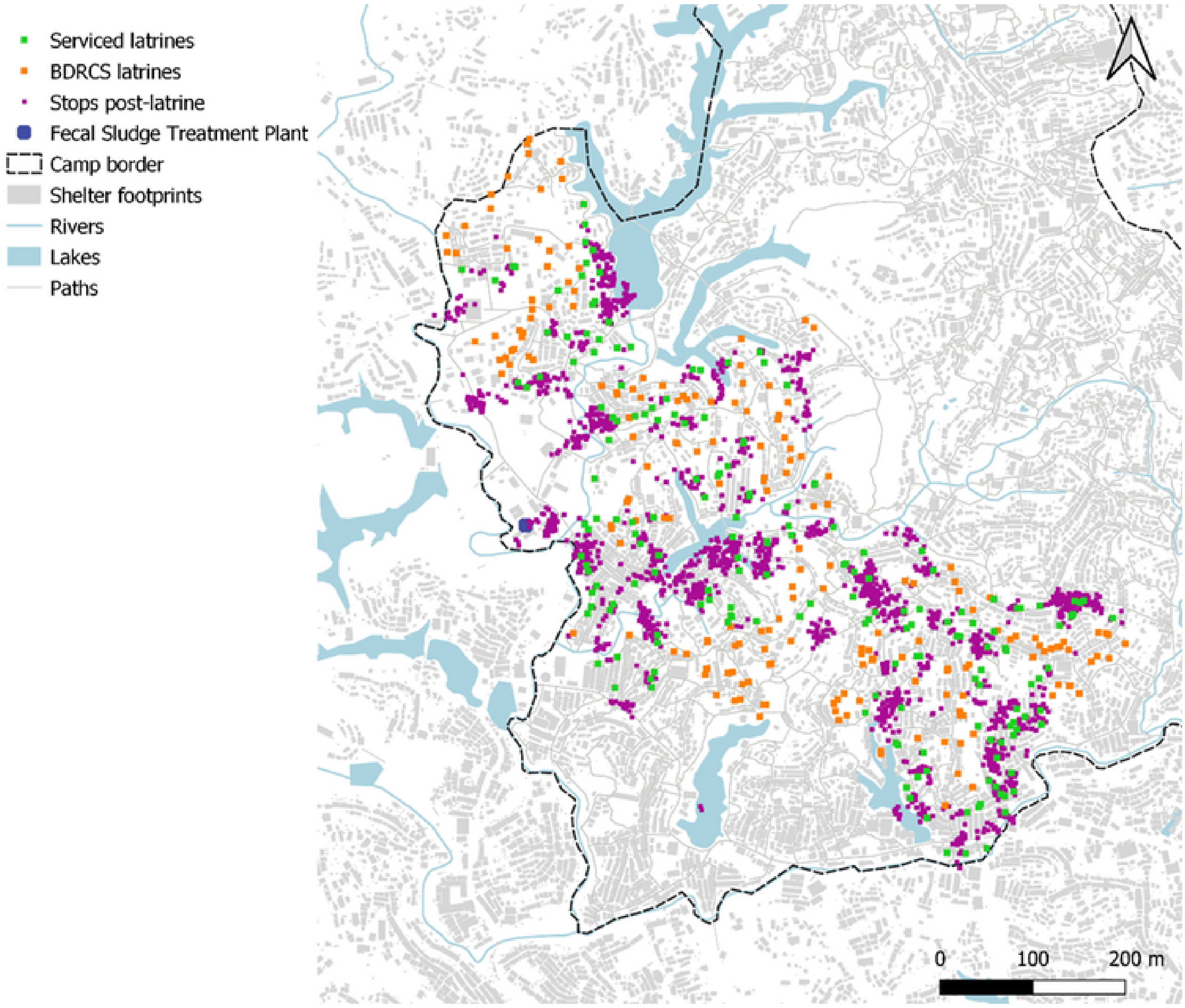


Figure 11: Map showing serviced latrines and stops after a latrine emptying event which did not occur near the FSTP [60]

When a latrine is serviced, it involves anywhere between 1 and 8 barrels worth of sludge being filled from that latrine and returning to the FSTP. In total 5247 trips were made with full barrels of sludge to the FSTP within these ten weeks, which equates to approximately 262.35 m^3 of sludge. As GNSS loggers were placed on 20 barrels out of the 24 used on a daily basis, this is an under-approximation of the total sludge transported.

Along with the GNSS data loggers, the desludging plans kept by the BDRCS provided some more information about the spatial and temporal pattern of the barrel emptying activities. There is no regular pattern to the frequency of emptying per block. It ranges from the block having been serviced 7 out of the ten weeks to not even once. There are major discrepancies between the collected data and the desludging plans, with the plans showing that M10 and M15 were never serviced with barrels. The desludging plans also indicate how many pits within the block were emptied, with L1 and M12 having the most pits emptied and having been serviced twice in one week on two separate occasions. These results are shown in Figure 12. Furthermore, the number of pits emptied was divided by the number of latrines per block to standardize the results (Figure 13). This map shows how blocks M13, K5, and L2 also have a high proportion of pits being emptied, alongside L1. In fact, K5 and L1 have a value of over 1 meaning some pits in these blocks must have been emptied twice during the research period. On the contrary, M12 and M20 have lowered in ranking due to a high number of pits per block compared to the pits emptied. Finally, the most consistently emptied blocks are M10 and M19, as they are serviced with pumps every Thursday. It is also important to note that the area around the FSTP does not fall into any block, therefore, these latrines do not feature in the desludging plan although they are recorded by the GNSS trackers if they are more than 40 meters from the FSTP.

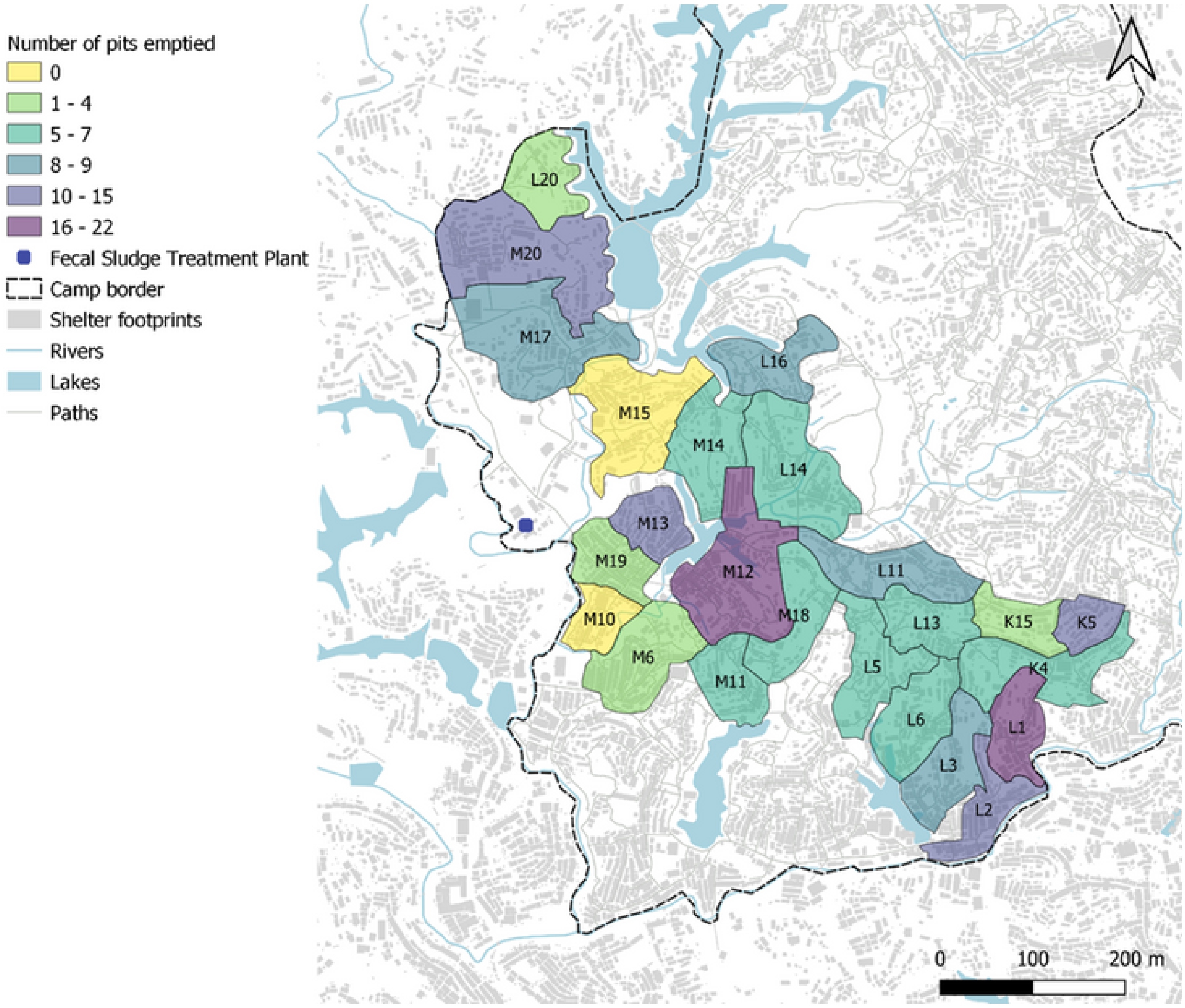


Figure 12: Data from desludging plans showing number of pits emptied per block [61]

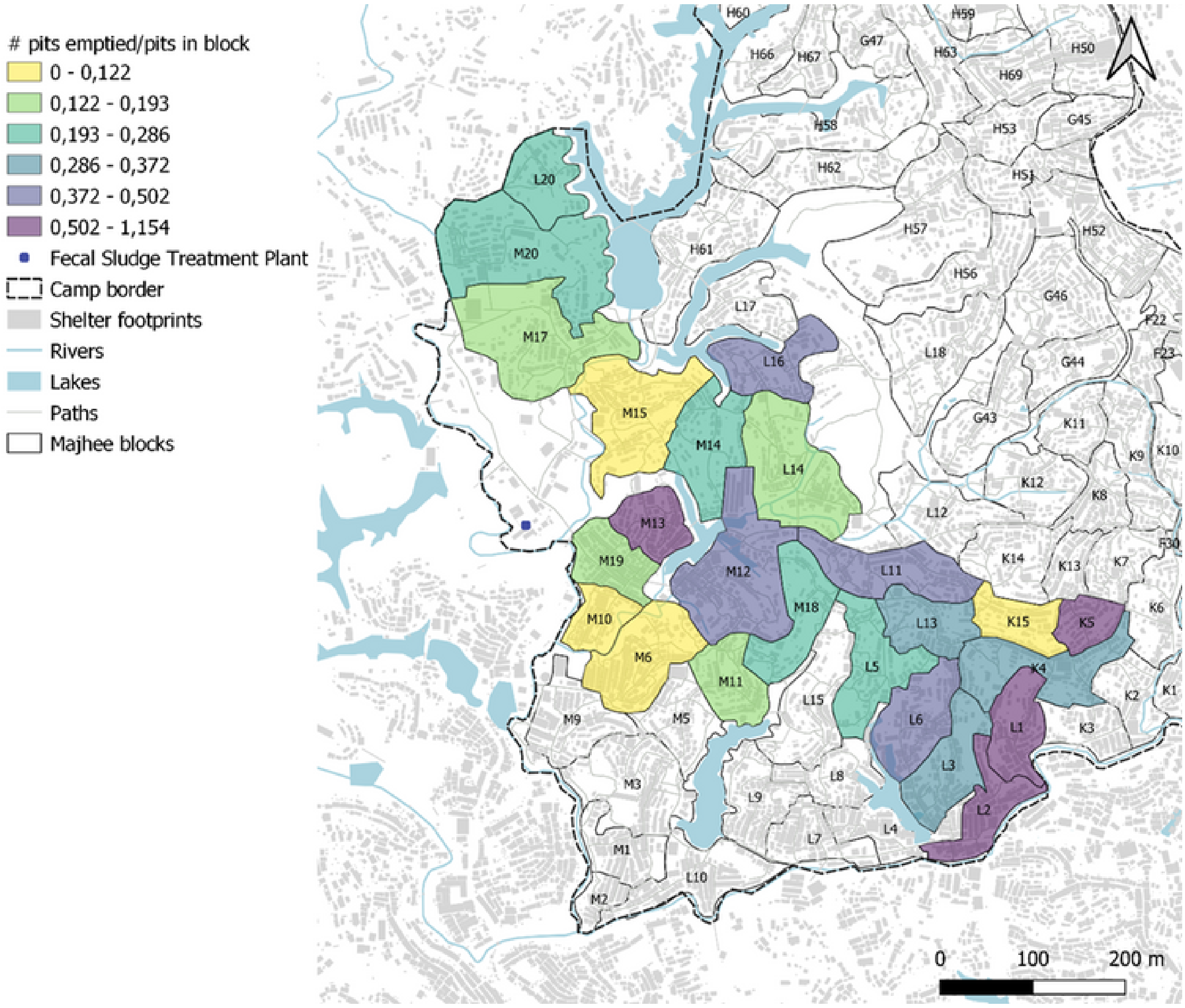


Figure 13: Data from desludging plans showing number of pits emptied per number of pits in a block [61]

Block L2 was mentioned in the interviews as a block that needed to be emptied frequently as it is far from the FSTP and is located at the bottom of a hill (Figure 14). This is confirmed with the desludging plan stating it was emptied 7 times, including twice in one week on two separate occasions. This can also be observed in the GNSS data. The interviews also unveiled that some discrepancies between the desludging plans and the GNSS data could be caused by the daily work plan being created with the desludging volunteers in the morning. Then, while following the schedule, if there is an urgent call for desludging from any other block, they immediately prioritize servicing that block. The interviews also highlighted that a latrine's location with respect to the many hills covering the camp is very important for sludge accumulation rate. All the paths and community buildings are located at the foot of hills. Therefore, latrines in these locations are not only used by surrounding residents but by anyone passing through the area. Figure 14 shows how the blocks in the south-east corner of the BDRCS area are very influenced by elevation. The desludging team also commented that blocks that are far away and high in elevation require the planning of rest times. Additionally, there is a limitation on the number of trips allowed to be carried out per day to these blocks. This shows that the desludging team struggles with large distances and elevation change.

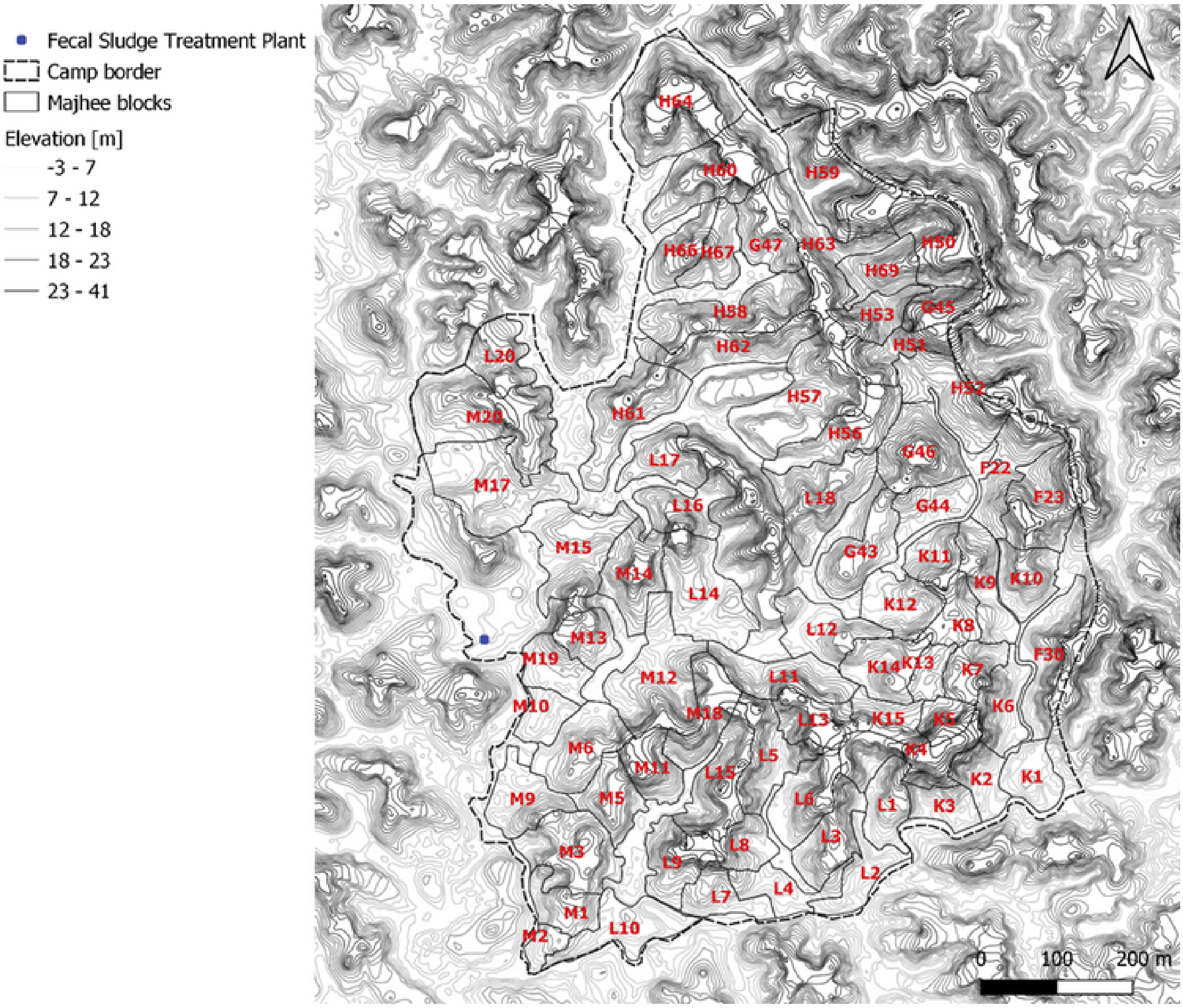


Figure 14: Map with contour lines showing elevation in each block [62]

Explanations for why the desludging activities took a certain spatial and temporal pattern were fundamental for this research. While not mentioned in the interviews, population density was a crucial factor to explore and a shelter density heat map was created (Figure 15). This shows that M19 and K5 fall in the most densely populated areas of the BDRCS service area.

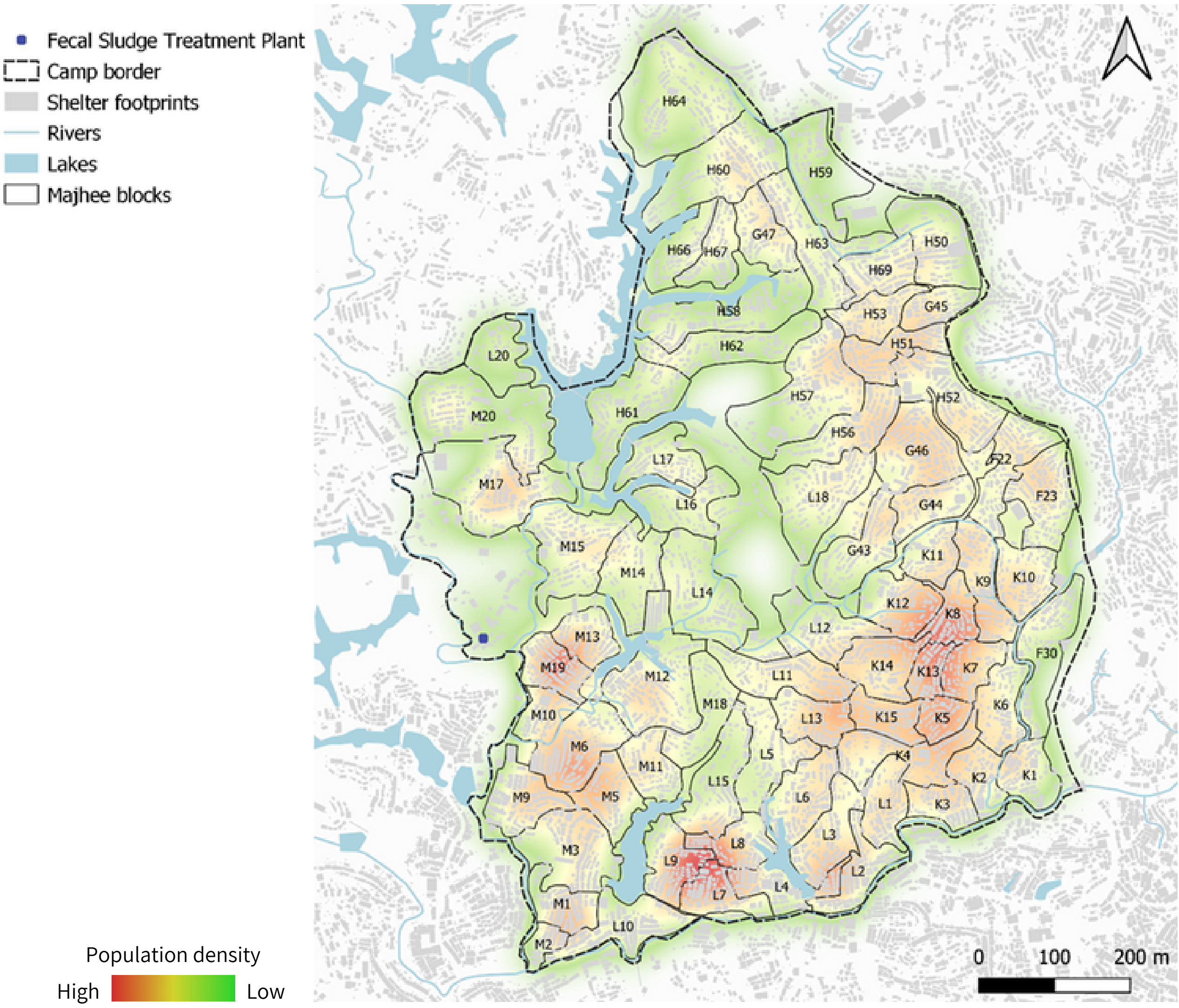


Figure 15: Heat map showing shelter density [63]

Stops were classified into four types: FSTP, stop pre latrine, latrine, and stop post latrine. Stops after the latrine are very interesting for this research as they could indicate fatigue or dumping at an undesignated site. There were 2644 stops classified as "stop_post_latrine" out of the total 37 039 stops identified, which is 7.14 % (Figure 11).

As shown in Figure 16, the chosen transportation routes can vary from the shortest path between the serviced latrines and the FSTP, with around 10 % of serviced latrine facilities only being reached using alternative routes. This map also depicts the slight inaccuracies in the GNSS data leading to different path widths which have no relation to the use frequency.

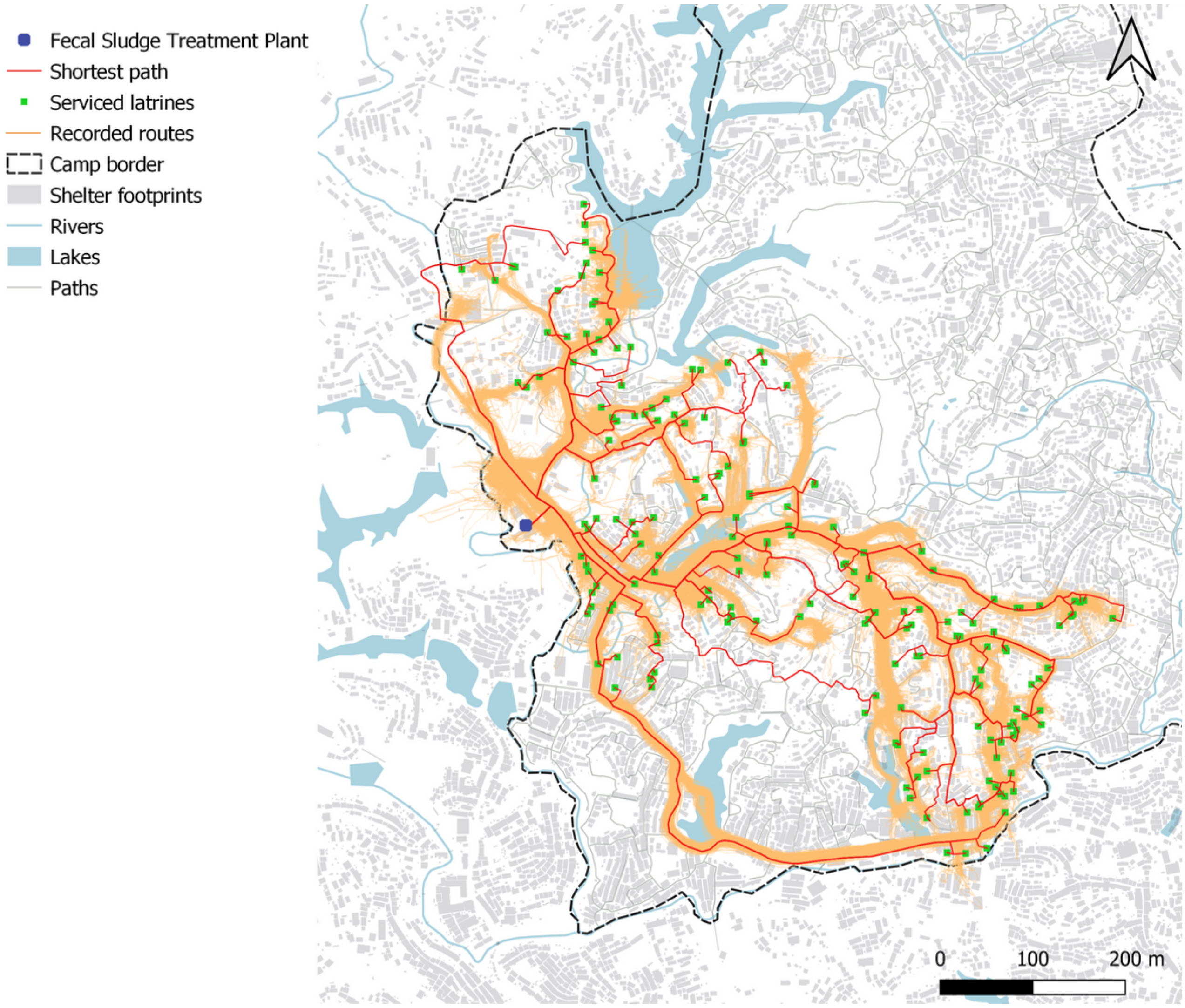


Figure 16: Map depicting QGIS calculated shortest path to serviced latrines in comparison to recorded paths [64]

Figure 17 shows the recurrence of the routes being taken by the desludging team, with the bold numbers representing the number of journeys which passed that point on the path network. As the values refer to every passing journey, this means that a path with a value of 222 should have had 111 full barrels carried along it. If the value is odd, this could be because that path segment was used in one direction and a different route was taken in the other direction. Randomized colors were used to highlight the multitude of occasions at which each path was used and depicts the slight GNSS errors for each of these routes following the same path.This map was initially produced for the optimization process in order to score the transfer stations higher if they are placed on one of the preferred line segments. The goal was to reduce the need for changes in the routing when adding transfer stations to the system. However, as the preferred routes are only available for the BDRCS serviced area of the camp and the optimization model is designed for the whole camp, the results from Figure 17 could not be used any further.

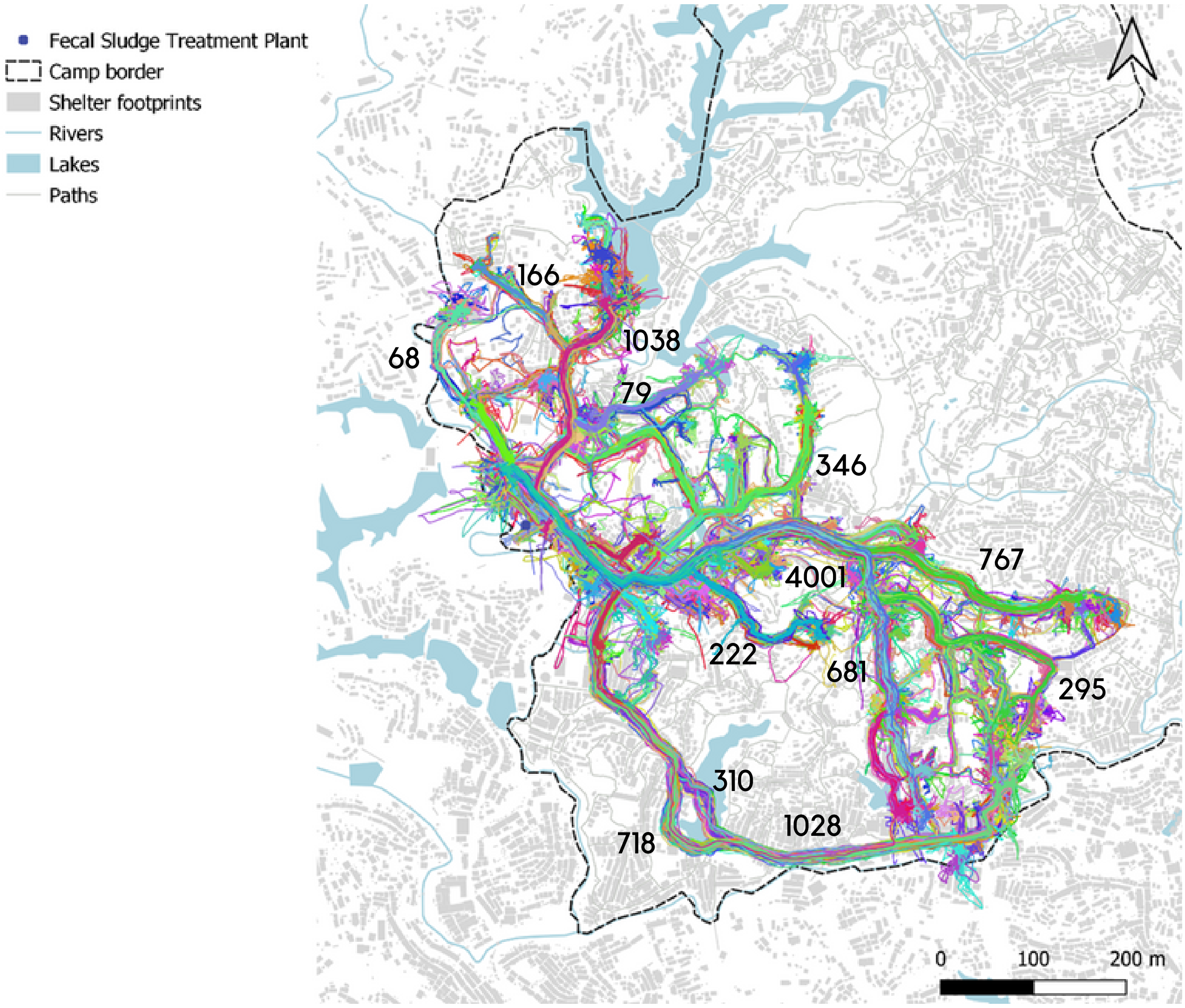


Figure 17: Recorded paths depicted in random colors to show recurrence of use of certain path segments [65]

4.1.2 Maximum Distance and Elevation Change of Transport

The analysis of the average velocity at which a full barrel of sludge is carried was completed in two different ways. The graphs in Figure 18 show the correlation of average velocity with both distance and elevation change. The average velocity was calculated for the whole return journeys from the latrines to the FSTP with full barrels of sludge. Average velocity is calculated from the velocities reported by the tracker, and not calculated based on distance and time. These results remain quite inconclusive with average velocity remaining quite constant irrespective of distance or elevation change. Therefore, the second approach included the calculation of the distance, elevation change, and average velocity data for 30-second segments of the return journey. These results are shown in Figure 19, with elevation change clearly influencing the average transport velocity, while distance still has a seemingly insignificant influence on the average velocity.

To further assess the relationship between each of these variables and average velocity, a simple Multiple Linear Regression Model and ANOVA test was carried out to see how each variable individually affects the average velocity. This assessment was carried out on the 30-second segment velocity data as Figure 19 showed it to be more conclusive. The solution obtained very high t statistic values and regression coefficients of 0.0858 for distance and -0.0704 for elevation change. This shows that both distance and elevation change have a significant influence on average velocity although the influences are quite weak. It also shows that the influence of distance is positive, contradicting expectations.

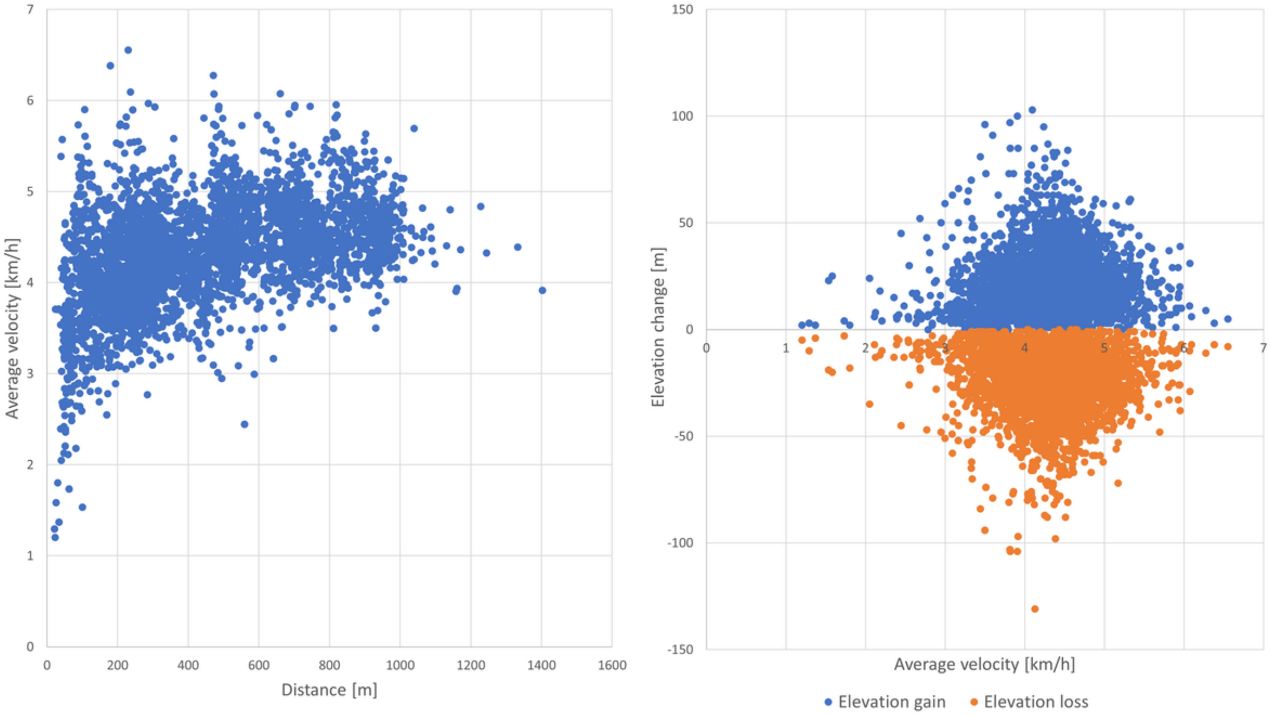


Figure 18: Comparison of average velocity with total travel distance (left) and elevation change (right) for whole return journey. An outlier was removed from the elevation change graph due to errors in the altitude data recorded by the GNSS tracker.

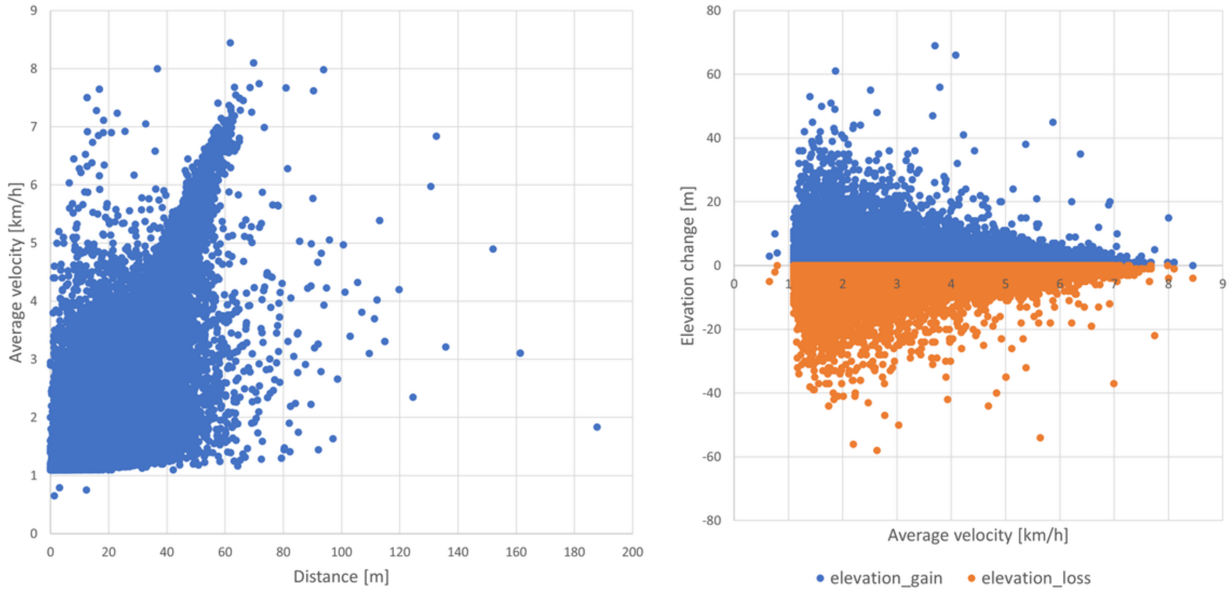


Figure 19: Comparison of average velocity with total travel distance (left) and elevation change (right) for 30 second segments of return journey

4.2 Optimization

4.2.1 Potential Transfer Station Sites

Using the constraints mentioned in the methodology, the potential sites depicted in Figure 20 were identified. It is interesting to observe the scarcity of potential transfer sites in the south-east quadrant of the camp, which could be explained by high shelter density in that region (Figure 15).

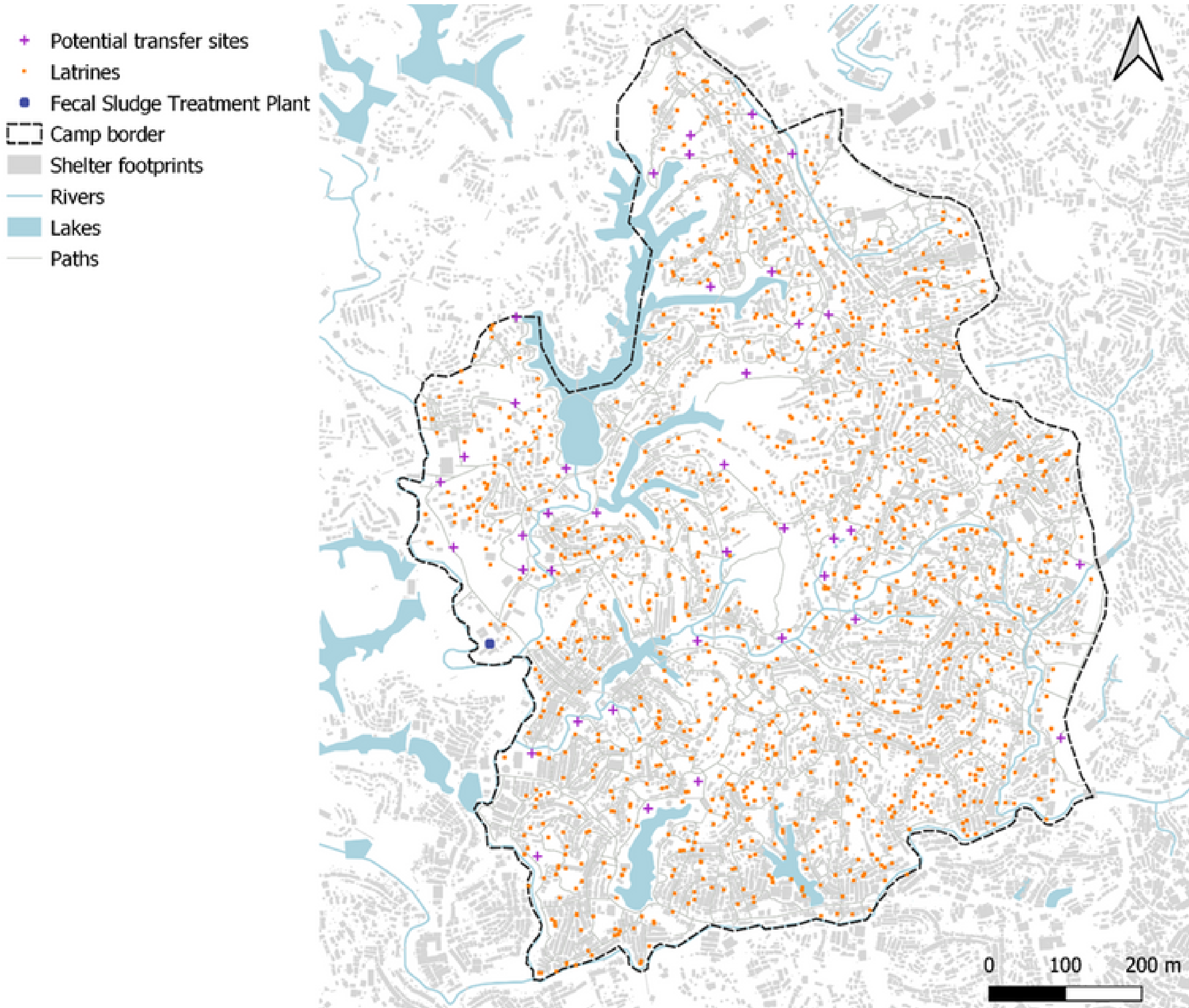


Figure 20: Potential transfer sites as a result of suitability analysis [66]

4.2.2 Optimization Results

4.2.2.1 Standard Model

The optimization model uses all the potential transfer sites found in the site selection as input values. The constraints of Zmax (maximum transfer station capacity in liters per day) and Dmax (maximum latrine to transfer station distance in meters) were set using the service coverage analysis results. The maximum, network-based, distance of a serviced latrine from the FSTP was 900 m. Therefore, this was set as Dmax. This serviced latrine is located in block L2, which was also highlighted as the most difficult block to service in the interviews. The transfer station capacity was set based on the total sludge allocated within the system which was calculated as 14 832 L/d. All the transfer stations combined should have the capacity to hold all the sludge in the system. For the set covering method, as the number of transfer stations was still unkown, Zmax was set to 15 000 L/d and the Zmin was left at 0 L/d.

The constraints were entered into the model and it was solved using XPRESS-MP. The set covering results showed that 3 transfer stations, including the FSTP, are needed to service the entire area. This value of two additional transfer stations was used as input for the p-median model. The Zmax value was also changed to 7500 L/d as the total sludge capacity was split over the two additional transfer stations in the system. Figure 21 shows the results of the set covering model with a total weighted transportation distance of 7742 km*L/d. The subsequent p-median model results in a total weighted distance of 4976 km*L/d and a total weighted elevation change of 958 km*L/d.

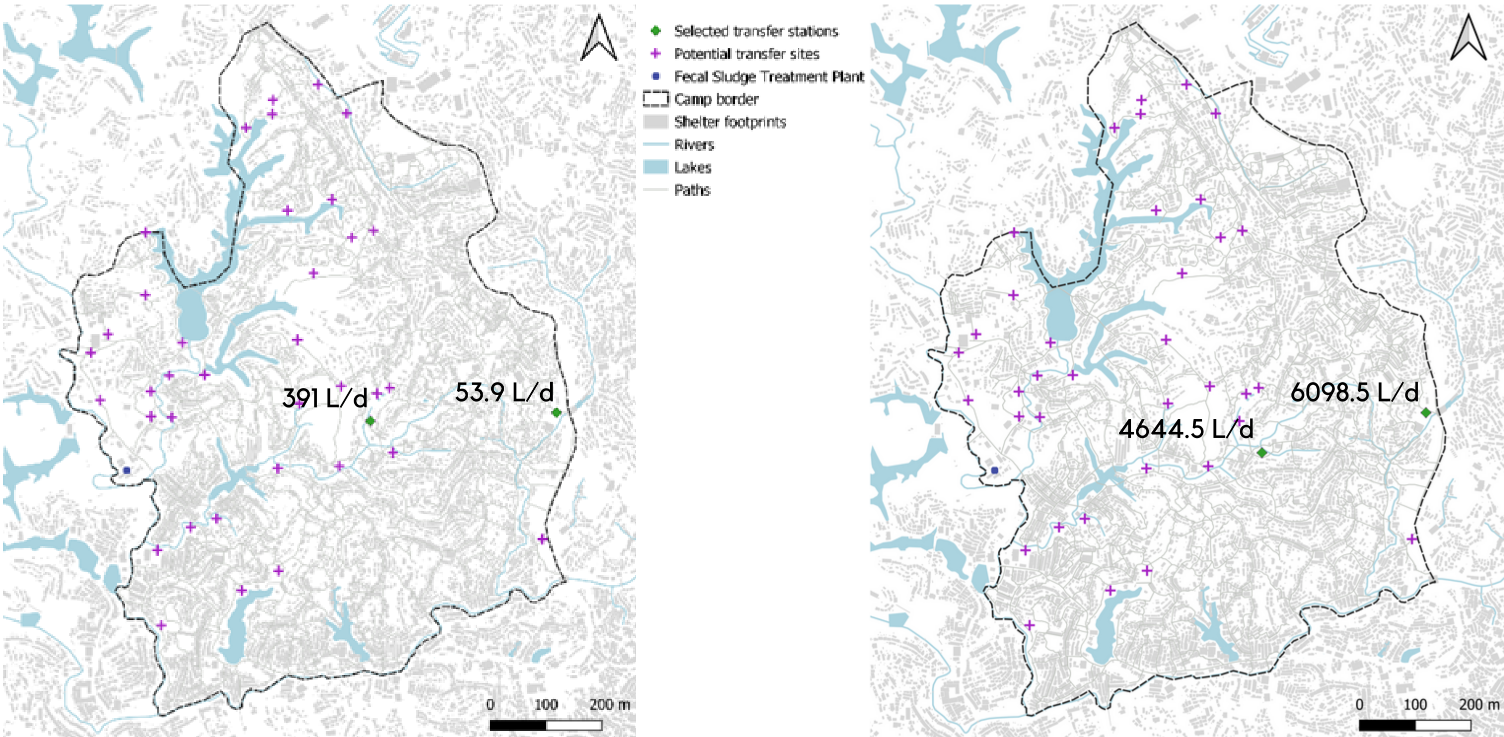


Figure 21: Results of optimization model including final capacity allocated to each transfer station with set covering on the left and p-median on the right [67]

4.2.2.2 Optimization of Weighted Distance and Weighted Elevation Change

The second optimization model also includes elevation change from the transfer sites to the FSTP. The goal is to prioritize transfer stations with minimal elevation change to the FSTP to make other transport modes, such as carts, a possibility. The constraints of Zmax (maximum transfer station capacity in liters per day) and Dmax (maximum latrine to transfer station distance in meters) remain the same as the first optimization model. Therefore, the set covering model does not change, as the objective function including elevation change is only used in the p-median model.

The alteration in the model occurs when minimizing for cost rather than distance in the p-median objective function. Cost is the sum of elevation change and distance, but requires the addition of weighting factors to ensure the influence of both variables is accurately represented. The weighting factors of ***a*** and ***b*** for elevation gain and elevation loss, as well as ***A*** and ***B*** for elevation change and distance were determined with the results of the Multiple Linear Regression Model and ANOVA test. First, the influence ratio between elevation gain and elevation loss needed to be assessed in order to have an accurate elevation change value. The test resulted in regression coefficients of -0.0962 for elevation gain and 0.0717 for elevation loss. These values are very similar when we ignore the negative sign due to the elevation loss always being negative. Therefore, the influence of the two variables is assumed to be equivalent. This means that no weighting factor was required in the calculation of elevation change. In other words ***a*** = 1 and ***b*** = 1. The regression coefficients for elevation change and distance were already mentioned in Section 4.1.2. With values of 0.0858 for distance and -0.0704 for elevation change. This shows that the influence of elevation change and distance should also be seen as equivalent in importance, although their effects are counteracting. Therefore, ***A*** = 1 and ***B*** = 1, so no weighting factors were ultimately used in the optimization model.

Using 3 transfer facilities (including the FSTP) and minimizing for cost leads to a p-median model result of a total weighted distance of 5207 km*L/d and a weighted elevation change of 157 km*L/d. The chosen transfer stations are shown in Figure 22. This shows a 231 km*L/d increase in overall weighted transportation distance and a 801 km*L/d decrease in weighted elevation change if we optimize for both distance and elevation change. Therefore, this second model has a lower overall weighted result. Thus, this solution is more optimal if both elevation change and distance are considered as important, or if average velocity is considered as important.

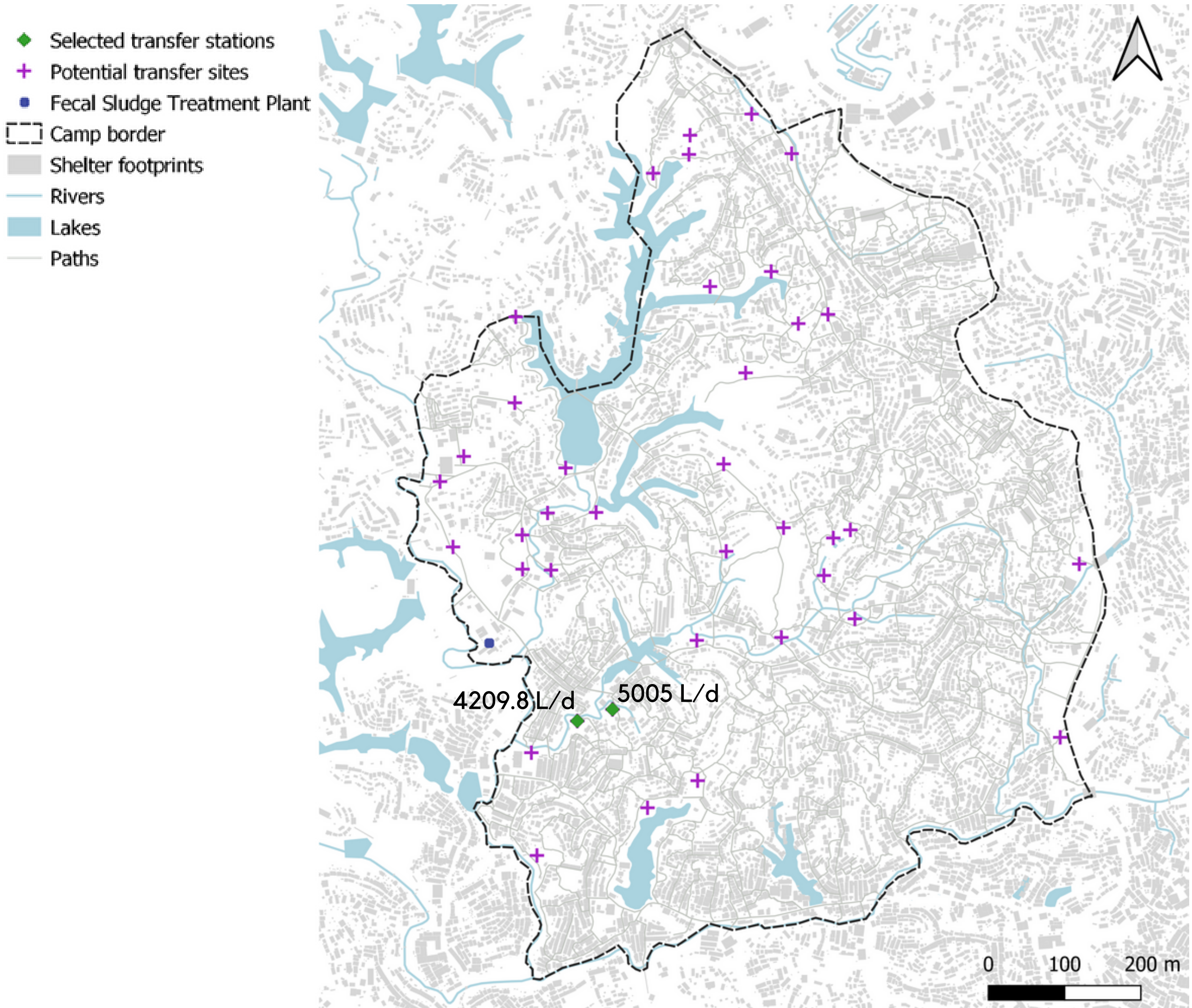


Figure 22: Results of p-median optimization model minimizing for both distance and elevation change [67]

4.2.2.3 Sensitivity Analysis

Building these optimization models required many decisions and assumptions which could influence the final result. Therefore, it is important to assess the stability of the results when the assumed factors are varied. All the sensitivity analyses were carried out on the final cost minimization model and only the fluctuation of the weighted distance is depicted in order to simplify the results.

Zmax and Zmin

The value chosen for Zmax of 7500 L/d was determined based on the total sludge produced per day divided by the two installed transfer stations. Zmin was assumed to be 0 L/d as no minimum limit seemed necessary. In Figure 23, both of these variables are altered individually to observe the influence of these value assumptions on the final weighted distance result. These results show that the model can only minimize weighted distance when it is not constrained by these variables. The optimal storage capacity value (Z) is shown to be around 5000 L/d.

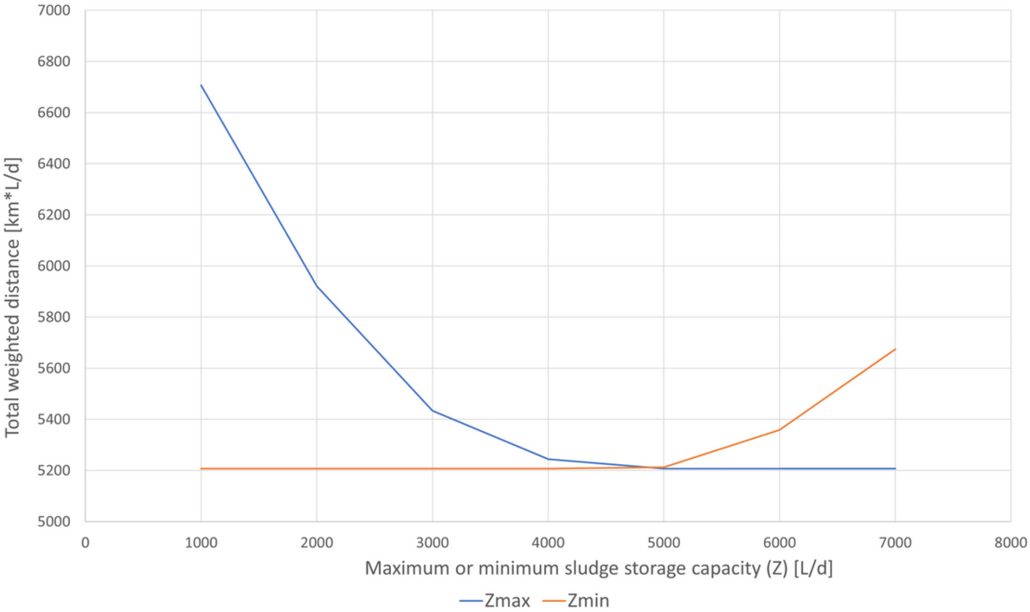


Figure 23: Influence of Zmax and Zmin on result stability

Dmax

The value of Dmax was set at 900 m based on the furthest latrine serviced by the desludging team and acts as a constraint on the optimization models. The model is invalid with a Dmax of 500 m as not all latrines are within 500 m of a proposed transfer station. At a Dmax of 1100 m all the sludge can be brought straight to the FSTP. Figure 24 shows how Dmax influences the set covering model result of the number of transfer facilities and subsequently the cost minimization model weighted distance result. The increase of Dmax causes a decrease in the required number of sites, which then restricts the p-median model further causing an increase in the total weighted distance. If more transfer facilities were used than necessary, the total weighted distance could be minimized further.

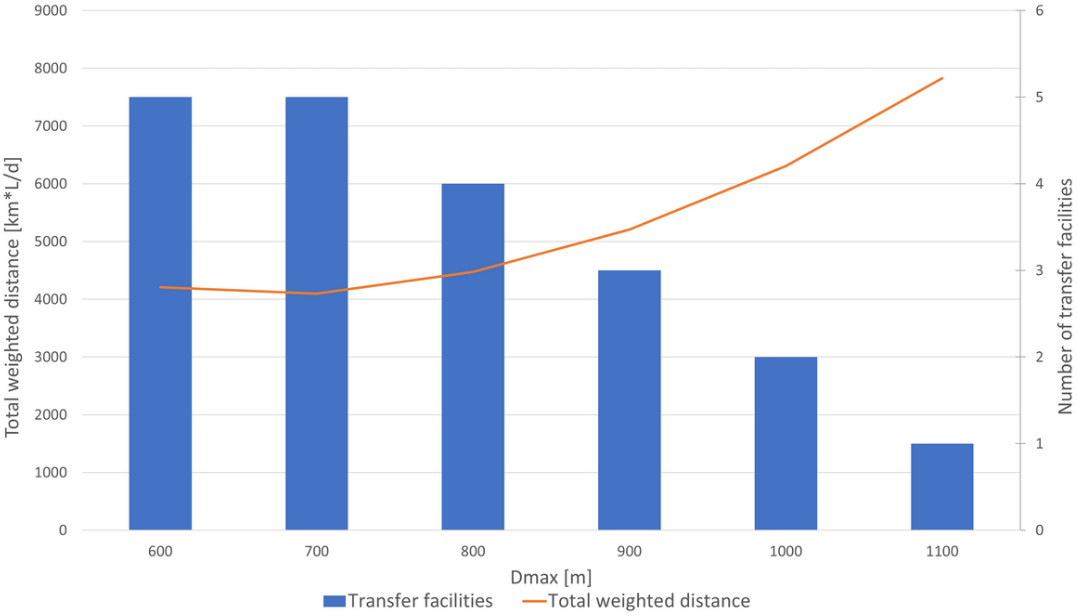


Figure 24: Influence of Dmax on result stability

Weighting Factor on Elevation Gain and Elevation Loss

An assessment was also made on the influence of the weighting factors on elevation gain and loss. The applied weights were 0, 5, 10 and 20, with the original model being built with no weight, which is equivalent to each being weighted 1. The weights were applied to only one of the variables at a time, leaving the other in its no weight state. The results of these weights are displayed in Figure 25 and show that the ratio between gain and loss has little impact on the final results. However, the weights do influence the ratio between elevation change and distance, influencing the final results.

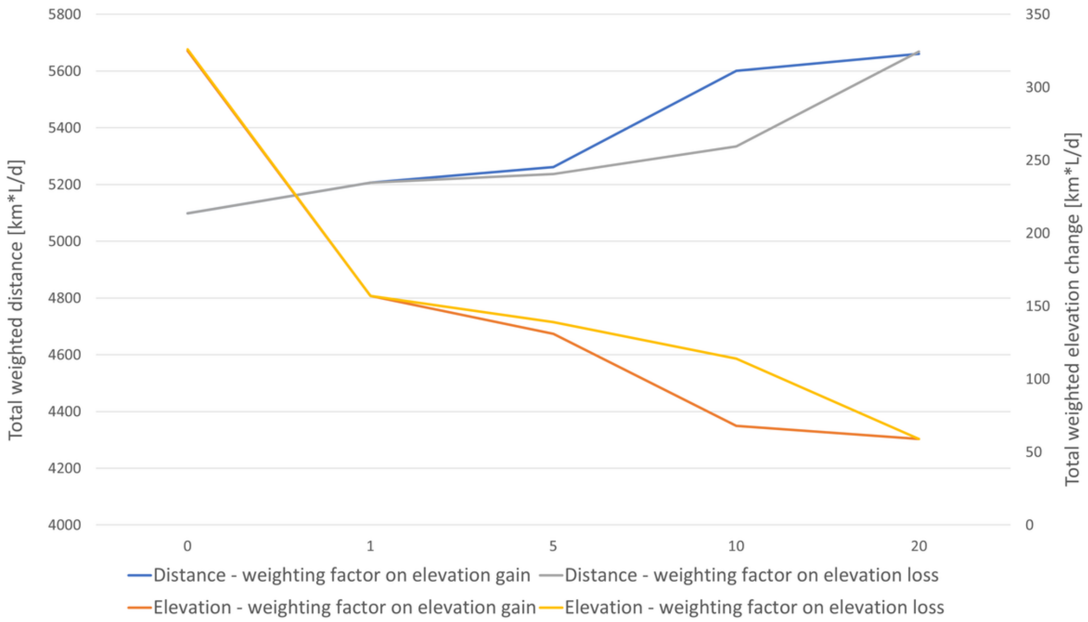


Figure 25: Graph showing the sensitivity of the results when elevation gain or loss are weighted

Weighting Factor on Elevation Change and Distance

Figure 26 shows the results of the weighting factor assessment on both elevation change and distance. Weighting elevation change leads to similar results as weighting either gain or loss strongly. More importance is placed on minimizing the weighted elevation change. Therefore, an increase in the weighted distance can be observed. The opposite effect can be observed when weighting distance. Moreover, when weighting distance with a factor of 20 the same result is obtained as applying a factor of 0 to elevation change. However, when a factor of 0 is applied to distance, the resulting elevation change is significantly smaller and distance is significantly bigger than applying a factor of 20 to elevation change.

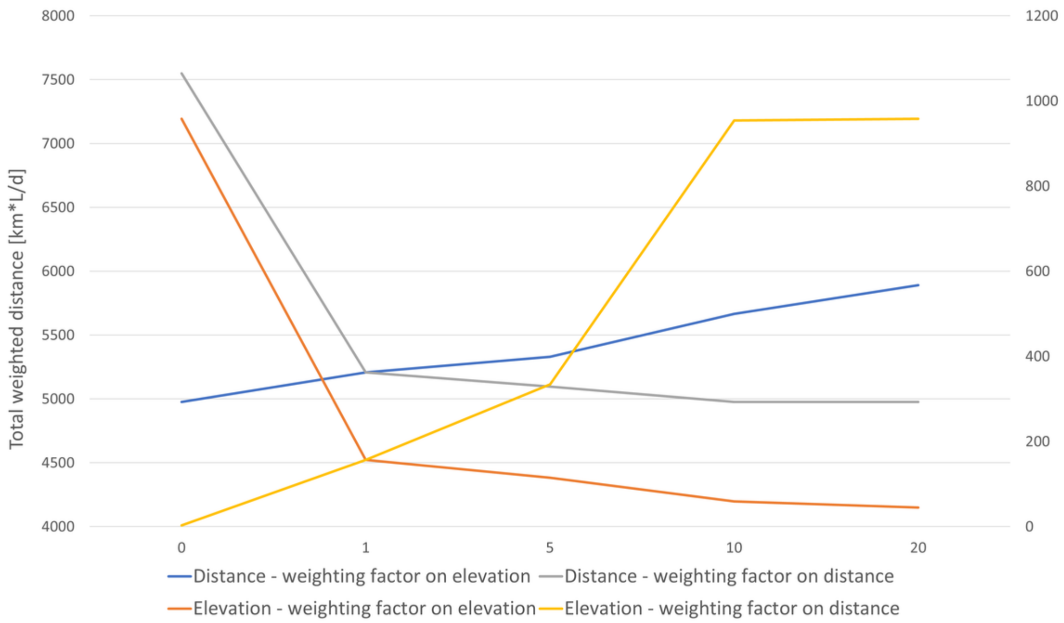


Figure 26: Graph showing the sensitivity of the results when elevation change or distance are weighted

4.2.3 Potential FSTP Site

The suitability analysis methodology to find a site for the new FSTP resulted in only one area of over 1000 m^2 available. In total, it has an area of 2339.94 m^2 and a perimeter of 329 m (Figure 27). Since the current FSTP has an approximate area of 3777 m^2 and a perimeter of 293 m, it is a reasonable assumption that this available site could fit a more optimized version of the current treatment system. Otherwise, the new FSTP could also be designed to have a smaller capacity. Although, the capacity of the current FSTP already seems like a topic of concern within the camp. As only one site was found, no optimization step was necessary for the FSTP. It is assumed that the new FSTP would have an equivalent service coverage to the current FSTP. Therefore, it would enable the majority of the camp to be desludged easily as the service coverage of one FSTP is approximately 43 %. If a new FSTP is built, the whole management system must be redesigned to redirect part of the sludge to the second FSTP. Additional coordination would also be necessary with the other NGOs desludging Camp 18 in order to design a more optimized allocation of blocks. Figure 28 shows the service coverage of both the current and proposed new FSTP. The service area radius was based on the straight-line distance of the furthest serviced latrine of the current system, which was 610 meters from the current FSTP.

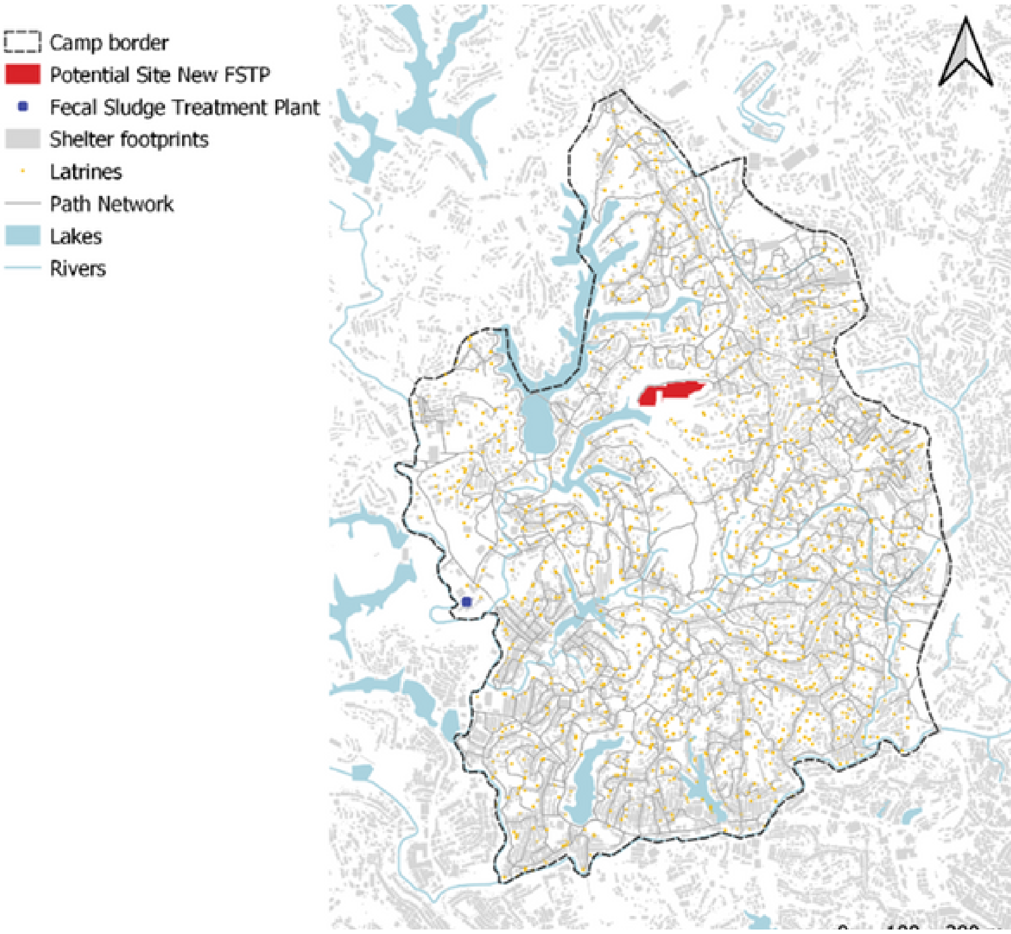


Figure 27: Map depicting only available site for a new FSTP [68]

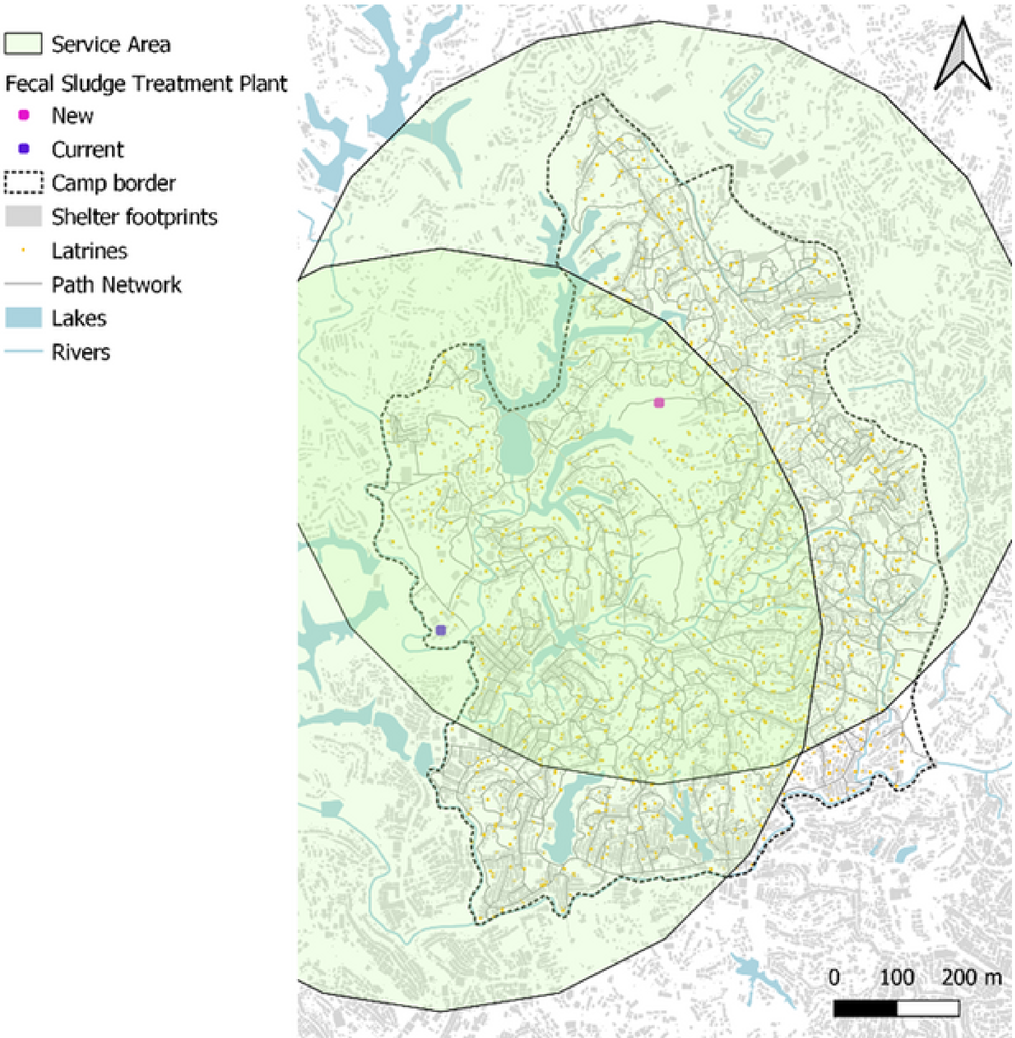


Figure 28: Combined service coverage of both FSTPs [68]

5 Discussion

5.1 Results

5.1.1 Service Coverage

Despite the large service coverage of the desludging teams with 49 % of the latrines in the BDRCS service area being emptied, this research shows that many latrines are skipped in the process. Therefore, some latrines might rarely be emptied. This could mean that the local community around unserved latrines is forced to find other means of disposing of the sludge. Such an outcome could be placing the health of the community and the environment at risk. Alternatively, the latrine coordinates provided by REACH as open-source data which were supposedly updated in January 2021, could be incorrect. If latrines were decommissioned or incorrectly recorded in the data and the desludging team is servicing all latrines in their service area, the ratio of people per latrine is far below the recommended standards within the Sphere handbook. The serviced area houses approximately 9200 people with 186 serviced latrines. Therefore, each latrine is used by around 50 people, which is significantly worse than the Sphere standards of 1 shared latrine for 20 people [69]. It is also important to note that the research period of ten weeks may not have been sufficient to observe the complete service coverage of the BDRCS desludging team. Moreover, in the interviews, it was mentioned that there are some latrines that were not serviced within this research period because the number of users is low. Alternatively, a latrine may not have been serviced if it is situated at the top of a hill. This can result in it being used less often or it can mean that the soil absorbs more water content from rainfall. It is hard to distinguish how accurate these explanations might be. It was also stated that other latrines are located next to lakes or streams causing the pits to fill quicker with water and diluting the sludge which needs to be collected.

This methodology does have some limitations which could result in slightly more latrines having been serviced than stated. For example, it is clear from the GNSS data that one latrine in block L15 was emptied. However, block L15 is not within the BDRCS blocks and serviced latrines were determined based on stops classified as “latrines” being within 10 meters of the BDRCS latrines. Therefore, this latrine was not considered as being serviced. Moreover, other latrines with slightly incorrect coordinates may fall too far from the recorded stops of the GPS data to be classified as serviced. However, these inaccuracies in the parsing method should be counteracted by latrines which are very close to each other. In such cases, the recorded stops might count multiple latrines as serviced when only one actually was.

When assessing the frequency of emptying a few conclusions can be stated. The desludging plans show that blocks L1 and M12 had the most pits emptied with 22 and 21 services respectively, which equates to being serviced on 9 and 8 separate occasions. The only other block with a similar amount of coverage was L2. Other blocks were serviced much less often, with M15 never being logged as serviced. There are discrepancies between the desludging plans and the GNSS data. These could be explained by unexpected schedule changes, as M15 was seemingly serviced on the 2nd, 10th, and 17th of January 2022. Another discrepancy is that the plans show that M11 was serviced on December 19th 2021 and January 10th 2022, however these are not present in the GPS data. As January 10th 2022 appears in both the discrepancies of M15 and M11, this could indicate that the desludging team was reassigned from servicing block M11 to service block M15. Block M10 also does not feature in the desludging plans, which validates the statement that it is serviced with pipes and pumps every Thursday by the desludging team. However, it is surprising that the other block, M19, which is also meant to be serviced by pipes according to the interviews, was serviced twice with barrels within the 10 week research period. This was twice in the same week which might indicate that on the Thursday of that week, the desludging team was unable to service M19 as usual.

In the interviews, block L2 was identified as the most difficult to service. However, many of the blocks the BDRCS services are located in the hilly area of south-east of Camp 18 (Figure 14). Most Majhee blocks encompass 1 or 2 hills, therefore the placement of L2 only at the base of a hill is quite unique, meaning it is often prioritized. When assessing the relationship of the desludging activities with shelter density, the recorded paths and the desludging plans show a concentration of desludging activities within areas with high population densities. Blocks M19 and K5 have the largest population density, and they also feature the most emptying events. M19 was desludged twice with barrels as well as being serviced by pipes every Thursday, while K5 had 15 pits serviced over the period of ten weeks. On the contrary, block M6 has a high population density but had only 2 pits serviced. Furthermore, while the least dense areas generally have low service rates, block M20 had 14 pits emptied. Therefore, the 1st hypothesis is rejected as there seems to be no relation between proximity to the FSTP and the desludging activities, while there is more of a correlation between the activities and population density. This result also matches the answers to the interviews where the desludging team describes multiple criteria which feature in their desludging plan.

The 7 % of unaccounted for stops after a latrine show little evidence of dumping at undesignated sites as they are often clustered around the latrine locations. The only 2 stops which are not close to a serviced latrine are located in a lake in the south-west of the camp. They occur on the regular path back to the FSTP and could be related to fatigue, crowded paths, or the requirement to have a short break when carrying full barrels of sludge. These 2 stops were completed by 2 different barrels at almost the exact same time and location, so it was most likely 4 desludging team volunteers who stopped to have a short conversation. These results lead to the rejection of the 2nd hypothesis and show that this publicly managed, manual transport, fecal sludge management system does not follow the Bangladesh statistics for dumping sludge in an undesignated site. The literature review showed that manual transport systems have higher tendencies of leading to undesignated dumping. However, this case study shows that undesignated dumping is a small or even non-existent problem in this region of the camp. This could be due to better sludge management practices in this camp, better working conditions for the desludging teams, or the high density of the camp leaving little opportunity for illegal dumping.

When analyzing the routes chosen to reach the latrines, around 10 % of the latrine facilities were reached by deviating from the shortest path. This can be explained using the topology of the camp. The latrines serviced in the south-east were reached using a path passing by the south-west as this mostly follows the valley floor and reduces elevation change (Figure 14). Moreover, there are many route choice variations for one origin-destination pair. This analysis was only assessing if the shortest path was taken even once, leading to a very low percentage. Finally, it was observed that the routes used by the desludging team do not always exist on the open-source path network inputted into QGIS. This is most likely caused by the presence of informal paths which skews the accuracy of our shortest path calculation.

Finally, the graphs assessing the average velocity traveled by the desludging team during the whole return journey to the FSTP with a full barrel of sludge show little correlation. Elevation change seems to have no influence on average velocity, while average velocity seems to increase with a greater distance traveled. Due to these inconclusive results, the return journeys were segmented into 30-second sections. On the one hand, this second assessment again showed a weak positive influence of distance of average velocity. On the other hand, elevation change clearly has a negative influence on average velocity. An increase in elevation gain or elevation loss have about the same reduction in average velocity. The Multiple Linear Regression model showed that both distance and elevation change have a significant influence on average velocity, albeit a small counteracting influence. It is unclear why average velocity increases with distance. One possibility is that the time to fill the barrels is more significant than the walking time between the latrine and the FSTP. This could cause crowded paths and slower walking velocities when emptying closer latrines. In conclusion, the 3rd hypothesis can be partially accepted as distance and elevation change have a significant impact on average velocity. However, the positive influence of distance on average velocity contradicts the hypothesis.

5.1.2 Optimization

The results show that 2 transfer stations and the FSTP are needed to satisfy the demand of the whole camp, while minimizing transportation distance to 900 meters. In the first model, the minimized total weighted transportation distance is 4976 km*L/d and the weighted elevation change is 958 km*L/d. The second model considers the influence of elevation with the result causing a 231 km*L/d increase in weighted distance but a 801 km*L/d decrease in weighted elevation. Considering that elevation change has an observable influence on average velocity, the second model is more appropriate for this context and only causes a small increase in the weighted distance. However, the proximity of the selected transfer stations to eachother as well as to the FSTP may cast some doubt on the real efficiency of the solution. The sensitivity analysis shows a clear otpimal Z value as Zmin and Zmax have a significant influence on the results. The assigned value of Dmax and the subsequent number of transfer faciltiies installed also results in significant variation of the results. Finally, applying a weight to elevation change or distance within the model also causes significant fluctuations in the results, while the influence of the ratio between gain and loss is almost negligible. Therefore, this methodology clearly has some limitations in its overall result stability, but all the values chosen for the research are justified to ensure clarity in the assumptions made.

The potential sites on which the transfer stations are placed were chosen to be greater than 4 m^2 and avoid environmental constraints such as slope and flooding. The proximity to houses remains a limitation as 10 meters may still not be sufficient to prevent negative effects on residents. Therefore co-creation sessions to address the NIMBY phenomenon might be necessary. The alternative of installing a new FSTP rather than adding transfer stations could increase the service coverage in Camp 18. However, the results do indicate that the south-east corner of the camp would remain hard to reach, increasing the likelihood that this area will not be sufficiently serviced. Furthermore, although the new FSTP site was chosen to avoid hazards such as flood zones and steep slopes, the site may still have some limitations. Flood zones are very close to the selected area, and with climate change, these flood zones are likely to grow making the selected site unacceptable for an FSTP. Moreover, the selected site is at the top of a hill, which hinders the transport of sludge to that location as elevation change negatively influences the desludging team’s average transport velocity. Finally, attempts were made to understand the current land use at this site, but the results from the field remain uncertain. There is a possibility that it is a former landfill that is currently being used by residents to grow crops.

At a late stage of this thesis, it was discovered that the BDRCS is planning to place septic tanks in different locations around the camp to increase the scale of sludge pumping from April 2022. It is unfortunate that the optimization model and results within this thesis were not tailored to this new infrastructure project. However, the results of the service coverage analysis and the optimization methodology proposed could be useful for siting these septic tanks.

5.2 Methods

The main limitation of this research is that the methodology itself may impact what is being studied. The desludging team knows that they are being tracked, as a consequence, they might alter their behavior. Therefore, if they were doing something wrong before, this data collection method would encourage them to change those practices to avoid punishment or losing their job. This means that there is no certainty that no dumping at undesignated sites occurred during or prior to this research. Furthermore, the open-source data used for this project to complement the collected data with the trackers were not completely accurate. It did not include certain footpaths and the coordinates for some of the latrines might be wrong.

The introduction of transfer stations within this fecal sludge management system in order to optimize it remains a debatable subject. While there is plenty of research about the potential utility of transfer stations within the conveyance of waste to ease transport, few have actually been installed. Moreover, among those installed there are limited cases where the transfer station was actually a success and remained a useful addition to the transportation system. The main example being the well-managed Sanergy transfer station in Nairobi [26]. A successful transfer station requires good design, as well as sustainable operation and maintenance. In the context of Camp 18, the transfer station must only be designed for manual carriers, rather than also for trucks. Therefore, the transfer station must be built at a low enough level to avoid spills and the holding tank needs to be well constructed to avoid leaking, which could cause surface water contamination [70]. Then, as the fecal sludge management system is public within the refugee camps, the transfer station cannot collect access fees to fund the operation and maintenance. Instead, access to the transfer station should be restricted to only the publicly funded desludging teams for safety.

Furthermore, camp management should set aside additional budget for sustainable operation and maintenance to prevent odors from being a problem for local residents [70]. Finally, the applicability of transfer stations in the context of this research also has another caveat. Due to the narrow path network, dense settlements, and undulating landscape across the whole camp, there is no opportunity to switch transport mode at a transfer station. This is usually done to increase transport efficiency. The transfer stations are only used to split the carrying journeys into shorter segments. Such an application of transfer stations has never been discussed in literature. However, the desludging teams have stated that they struggle to service the latrines further from the FSTP. Hence, it is a reasonable assumption that transfer stations could increase the overall service coverage of the desludging team. In conclusion, while the introduction of transfer stations is deemed appropriate for dense urban areas such as refugee camps, a pilot study would be necessary to assess their true influence on such a fecal sludge management system.

NIMBY is a common phenomenon in facility siting problems, especially with facilities that risk causing a nuisance for locals such as odor or noise. While these facilities often provide essential services to residents, their siting will often be seen as unfair which will lead to dissatisfaction [25]. It is also important to highlight that scientifically planning the location of transfer stations is important for reducing costs of a fecal sludge management system [25]. Therefore, NIMBY should not prevent these analytical methods from being used. The research by Holm et al. (2021) explored the forms of resistance as part of NIMBYism that could develop around the implementation of various waste management infrastructures [71]. They found that the Nkhorongo liquid waste facility in Mzuzu City, Malawi, only received reports of odor concerns from a private school 1 km away, while no complaints came from the surrounding community [71]. This could indicate that complaints would not arise after the installation of a fecal sludge transfer station in Camp 18. However, research unveiled an unexpected risk of placing transfer stations in the middle of communities. When left unguarded, residents collected untreated sludge from the ponds within the Nkhorongo facility, without any personal protective equipment, in order to use the sludge as fertilizer [72].

Building the optimization model also required making choices. In order to minimize both elevation and distance within the second model, elevation change had to be calculated along the same shortest-distance routes. In the optimization, new origin-destination pairs are never considered. Therefore, a path that could circumvent hills to minimize elevation change might be a better overall solution than using the shortest path, but this cannot be checked due to the input data format. Elevation has also only been added to the model for the journeys from the transfer sites to the FSTP. This is due to the complexity of calculating the elevation matrix, which can only be done from point to layer rather than from layer to layer in QGIS. Therefore, the process would have had to be repeated 38 times for each transfer site in order to minimize elevation from latrines to sites. This was deemed unnecessary as the most significant part of the carried journey, also with the largest load, is from the sites to the FSTP.

Based on the literature review of optimization models in the same field, other potential approaches could have been taken for the optimization portion of this research. For example, Chen et al. (2021) maximized the distance between transfer sites and settlements [25]. The addition of such an objective function within the optimization model might have led to a more appropriate result regarding the NIMBY phenomenon. However, such a model would be very restrictive and since the camp is so dense, it is unclear whether a real improvement would be visible within the result. The work of Habibi et al. (2017) included a minimization of both total cost and maximum cost [44]. This would have been a valuable addition to the research as instead a maximum distance constraint was added to the model. The value for this constraint was estimated from the service coverage data. The sensitivity analysis shows that the value selection has a significant impact on the results, therefore a minimization of maximum cost could have reduced this dependence of the results on a constraint value choice. Finally, Asefi et al. (2015) did not use optimization only to locate transfer stations, but also to select the routes taken to transport waste to these transfer stations using a location-routing problem [46]. Such a methodology would be a more complete optimization of the fecal sludge management system. However, it is unlikely that the desludging teams would follow the optimal routes found rather than using their informal, more efficient, and preferred paths.

5.3 Recommendations

While this research promotes the use of transfer stations, there are very few cases where such installations have been successful. Furthermore, transfer stations were introduced within this research as a solution to shorten transportation distances rather than change transportation modes. This means that transfer stations could be redesigned to meet this alternative use case. Rather than emptying the barrels into a large containment at the transfer station, the transfer station could be a small locked structure where barrels can be left. When emptying a latrine, the full barrel would be transported to the transfer site and left in the structure to be exchanged for an empty barrel. Then other team members would complete journeys between the transfer site and the FSTP. This would reduce the risk of sludge settling in the transfer station containment and might simplify the management of the transfer station.

Another alternative would be to change the mode of transport for the journeys from the transfer stations to the FSTP. Currently, the BDRCS uses pipes and pumps to transport sludge from the two closest blocks to the FSTP. Overground piped networks have also been used on a limited scale for transportation of fecal sludge in Camps 3 and 4 by Oxfam. However, the application is limited to short distances, straight lines, minimal elevation change, and often the pipes are raised above the ground. All these constraints are to reduce the chance of ware on the pipes and leakages. While this piping collection system could be further expanded, based on learnings from other camps, it would not be feasible for the blocks furthest away from the FSTP. Alternatively, minimizing elevation change between the transfer sites and the FSTP could open up the opportunity for other transport modes such as sludge carts, rolling the barrels, or simply carrying more barrels at once to increase the transport capacity. A pilot study would need to be carried out to check whether there is an increased efficiency compared to current transport times per barrel when carrying more sludge per trip.

Other interventions can also be explored to improve the service coverage of the fecal sludge management system in Camp 18 and increase the capacity of the FSTP. These include improving the performance of the existing FSTP or installing decentralized treatment plants [33].

5.4 Further Research

There are large amounts of data available in Camp 18 that make it ideal for further research. To better understand the specific demand for a greater FSTP service coverage, it would be useful to quantify the excreta production for the whole camp [28]. With this information, an analysis could also be done to estimate the actual toilet requirement by exploring a demand-centric methodology and identifying places for new latrines [14]. The Sphere standards would also be fundamental for determining the placement and number of latrines necessary [69].

Furthermore, alternative data collection methods could be explored to better understand the system or to have less influence on normal practices. One means of achieving this would be to track the fecal sludge itself rather than the barrels that transport the sludge. RFID tags could be dropped into all the latrines within the camp. Then a scanner could be installed at the entrance of the digester that records a passing tag when the barrel transporting the sludge is emptied at the FSTP. This method checks whether sludge from every latrine really reaches FSTP, and therefore could discretely monitor the undesignated dumping events.

This research could be developed further with the additional information gained from in-depth interviews with the desludging team and residents. The questions included in the following survey were inspired by the literature review, with particular mention to the work of Sagoe et al. [9] which highlighted pertinent questions to ask the desludging team.

Desludging team

1. How often do you find latrines full?
2. How many latrines do you empty in a trip?
3. Is your barrel always full when returning to the FSTP?
4. Do you usually follow the emptying plan created based on the requests?
5. Do you sometimes dump collected FS directly into the environment?
6. Do you alter your emptying schedule and routes in the rainy season?
7. Please provide us with a difficulty ranking per latrine you emptied?

Residents

1. How many people do you share the latrine with?
2. How often do you find your latrine full?
3. How often is your latrine emptied?
4. When do you request for your latrine to be emptied?
5. How often do you open defecate because the latrine is full?
6. Do you believe the fecal sludge is always brought to the treatment plant?
7. Have you adapted your latrine so that it can never be completely full, as it leaks to the environment/informal sewer?

6 Conclusions

Camp 18 of the Cox's Bazar refugee camp has over 27 000 inhabitants and 9 % of these residents have stated that their main experienced sanitation problem is full latrines. Therefore, the goal of this thesis was to assess the service coverage of the camp's fecal sludge management system and optimize it to ensure all latrines are adequately serviced. With the help of the Bangladesh Red Crescent Society (BDRCS) management and desludging team, primary data was collected for ten weeks within the camp using GNSS data loggers. This data was supplemented with weekly desludging plans and interviews with the desludging team to gain a complete overview of the fecal sludge management system and its performance. In order to optimize the system, the concept of transfer stations was adopted in order to shorten the distance of each sludge transport journey. The overarching research question for this thesis was: To what extent can GPS data collection and spatial decision support systems be leveraged to optimize fecal sludge transport in Camp 18 of the Cox's Bazar Refugee Camp? Within the assessment of the current service coverage of the Camp 18 fecal sludge treatment plant (FSTP), it was discovered that the BDRCS only services 24 of the 50 Majhee blocks within the camp. The rest are serviced by other NGOs that only partly use the BDRCS FSTP. This thesis focuses on understanding the sludge carrying capacities of the desludging team in order to deduce their service coverage limitations. The fecal sludge management system was then optimized with the goal of ensuring that the whole camp can be serviced by the BDRCS desludging team.

The results of this research show that the spatial and temporal pattern of the latrine emptying process has unknown influences. Only 49 % of latrines in the service area were emptied during the research period, while some latrines were serviced multiple times. This raises the concern that latrines are either full or decommissioned, potentially resulting in around 50 people needing to use only one latrine. The first hypothesis was rejected, as the desludging team prioritizes servicing areas with a high population density over areas closer to the FSTP. However, with the complex prioritization technique used to make the weekly desludging plan, it is not possible to validate that the prioritization is equitable and fair. To assess this, future research could conduct interviews with residents or take field observations of sludge accumulation in latrines.

The field of fecal sludge management, and particularly systems involving manual sludge transport providers, have a high tendency for sludge to be illegally dumped at an undesignated site. The second hypothesis within this research was that 20 % of sludge collected in Camp 18 would be left unaccounted for. The results found that 7 % of return journeys from a latrine included an unaccounted for stop. However, there is little to no evidence that these represent sludge dumping in undesignated sites as they are all in close proximity to latrines. The rejection of the second hypothesis might have been caused by the dense environment and the fact that the desludging activities are publicly managed. Moreover, the use of GNSS data loggers made this research quite intrusive to the desludging team, possibly influencing them to diverge from their usual behavior.

Moreover, the influence of distance and elevation change on average velocity was assessed in order to determine the limitations of the desludging team. The GNSS data analysis results show that elevation change has a significant negative influence on average velocity, while distance has a significant positive influence on average velocity. Therefore, the third hypothesis was only partially accepted as the positive influence of distance was unexpected. On the contrary, the interviews supported the hypothesis, highlighting that latrines at high elevations and far from the FSTP are the most difficult for the desludging team to service.

An optimization model was developed to minimize the total weighted distance within the transportation system, while a second model explored how the results would change if elevation change was also minimized. The maximum latrine to transfer station distance was limited to 900 meters. This resulted in the need for two transfer stations as well as the FSTP to service all of Camp 18. Moreover, the model minimizing both distance and elevation change is most suitbale for the research context but obtained the a debateable result for the placement of these transfer stations. Alternatively, there is a suitable site for a new FSTP, but the south-east corner of the camp would not be serviced sufficiently.

This research has shown that the context of a publicly managed, manual transport, fecal sludge collection system within a refugee camp is extremely unique. Therefore, the methodology was designed to understand this system in depth before attempting to optimize it. The use of primary spatial data collection is rare within developing countries, with research usually relying on interview-based methodologies. This research demonstrates that primary spatial data in an emergency context can provide valuable insights and complement interview-based methodologies. It allows the researchers to gain a strong contextual understanding of the area without the risk of miscommunication skewing the results. Therefore, the versatility of the research approach proposed within this thesis makes its application suitable for many types of infrastructure siting projects in developing contexts.

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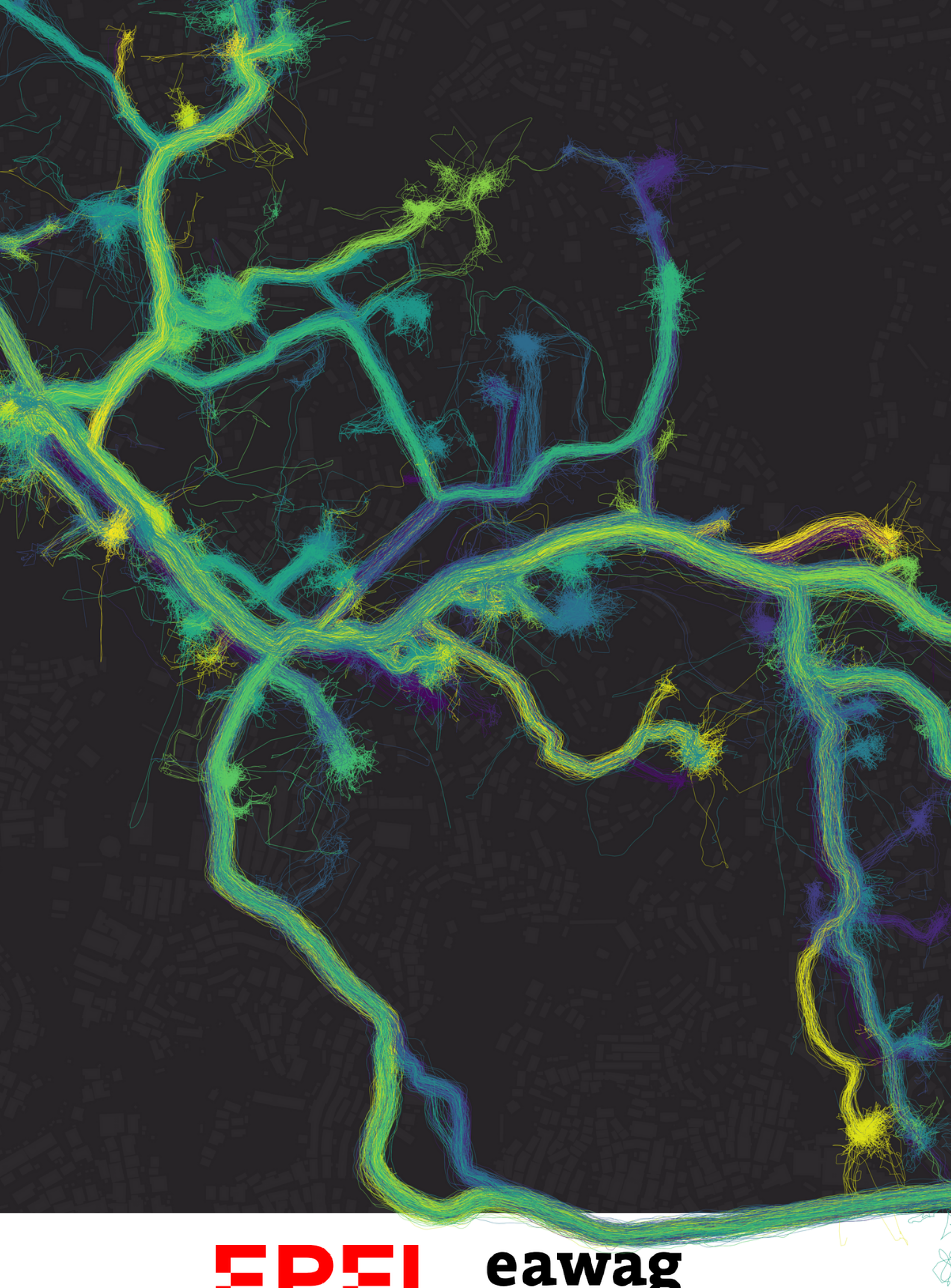

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