Department of Urban Engineering

Graduate School of Engineering

The University of Tokyo

2022

Master's Thesis

Spatial optimization of a portfolio of centralised and decentralised technologies for strategic planning of sustainable sanitation

July 2022

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Abstract

When planning sanitation systems for developing regions with heterogeneous settlement characteristics, it is desirable to consider a portfolio of solutions allowing to select the most appropriate for a given location. This study was built upon the proposition that a more sustainable sanitation service can be provided by considering a portfolio of centralised and decentralised sanitation technologies. In this study, a framework was developed for spatially explicit evaluation of sanitation system alternatives in terms of their economic, environmental, and social benefits. Data-driven and spatial analysis-based methods were employed to evaluate the suitability of sanitation system alternatives to a location. The annual cost was considered as the metric for economic assessment and the expected rate of adoption for social assessment. For assessment of environmental suitability, four metrics were combined: the quantity of wastewater inflow acceptable for on-site disposal, suitability of soil characteristics for on-site disposal, risk of water pollution, and opportunity for water reuse. Applying the evaluation framework to a study area in Sri Lanka which has heterogenous settlement characteristics, sanitation plans with optimized spatial distribution of alternatives were generated, for different planning scenarios with different development priorities. The assessment framework was implemented in an interactive sanitation scenario explorer, intended as an aid for decision making, participatory planning and education for sanitation planning. In most sanitation development scenarios considered in this study, the optimum sanitation plan was found to be a combination of centralised and decentralised technologies, supporting the initial proposition.

Acknowledgement

This thesis is the finalising work of my master's studies in Urban Environmental Engineering at the University of Tokyo. Successful completion of this work was made possible by the continuous encouragement and valuable guidance of many people.

I would like to express my immense gratitude to Professor Kensuke Fukushi, for his excellent advice, allowing room for my own ideas yet providing clarity and direction whenever I needed it. His exemplary style of teaching and supervision was a constant source of inspiration for me. I am also deeply grateful for Associate Professor Kiyo Kurisu, for her invaluable advice and kind encouragement. My gratitude extends to the many professors of the departments of Urban Engineering and Civil Engineering, from whom I had the privilege of learning and receiving valuable advice. The University of Tokyo gave me numerous opportunities to grow and develop as a person and as a scholar. I will cherish the life-changing experience I have had in this wonderful place of learning.

I lovingly remember my family and friends who were always close to heart despite being oceans apart, whose love and encouragement was a beacon for me in tough times.

I am thankful for the developers of the many free and open-source software and datasets I used in this research, whose incredible and underappreciated work is a testament to the humanity's ability to strive for the common good. I am also deeply thankful for the many individuals and organisations, especially the National Water Supply & Drainage Board of Sri Lanka, for sharing valuable insights and information that were instrumental in my research.

I express my sincere gratitude for Asian Development Bank for financially supporting my stay in Japan. My gratitude extends to the people of Japan, whose generosity enabled me to fully apply myself to learning and research. I owe my gratitude to the people of Sri Lanka, whose toil and sweat afforded me an excellent education that is the foundation of my academic journey.

Abbreviations

DS	Divisional Secretariat
BOD	Biochemical Oxygen Demand
BOQ	Bill of Quantities
CLUES	Community-Led Urban Environmental Sanitation
CSP	City Sanitation Planning
DEM	Digital Elevation Model
DEWATS	Decentralised Wastewater Treatment Systems
FSM	Faecal Sludge Management
FSTP	Faecal Sludge Treatment Plants
GIS	Geographic Information System
GND	Grama Niladari Division
HAND	Height Above the Nearest Drainage
HRSL	High Resolution Settlement Layer
JMP	WHO/UNICEF Joint Monitoring Program for Water Supply, Sanitation and Hygiene
LKR	Sri Lankan Rupee
MAUP	Modifiable Areal Unit Problem
MCDA	Multi Criteria Decision Analysis
MDG	Millennium Development Goal
NWSDB	National Water Supply & Drainage Board
PCA	Principal Component Analysis
PS	Pump Station
SDG	Sustainable Development Goals
SDM	Structured Decision Making
SuSanA	Sustainable Sanitation Alliance
WWTP	Wastewater Treatment Plant

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1 Introduction

Sanitation is a cornerstone of human development. On its own, access to good sanitation allows people good health, safety, dignity, privacy, and convenience. It also supports the achievement of other development goals such as poverty reduction, health, education, and equality. Despite the remarkable efforts of the past decades, providing access to high quality sanitation services for everyone remains a challenge for the world. Sanitation intersects many other key development issues such as poverty, health, gender, environment and urbanization and that improvements in sanitation can provide dividends in other interconnected issues.

Ambitious targets have been set for sanitation at global and national levels, such as the target of universal access to adequate and equitable sanitation by 2030, as set in the Sustainable Development Goals (SDG) of the 2030 Agenda (UNSD, 2022). Achieving such targets requires not only tremendous commitments of finances, resources, and political will but also fundamental changes in approach because it is unlikely to be achieved with current trends of improvement (UN Water, 2021). Hutton and Varughese, (2016) report that the capital investments required to achieve the SDG water supply and sanitation goals (Target 6.1 and 6.2) amounts to about thrice the current levels of investment. Low-cost methods that can be implemented faster at large scale are therefore needed to bridge the massive gaps in sanitation service in developing world.

Numerous technology alternatives are available at different stages of sanitation value chain, from toilets to final disposal or usage of treated sludge and effluent, with varying levels of technological sophistication. Centralized sewerage systems are the conventional approach to sanitation. While costly to build and operate, these systems can provide excellent pollution control and are suited well for managing high rates of wastewater generation in dense urban areas. However, in many developing countries largescale centralized sewerage projects have failed to provide the intended benefits because due to reasons such as poor maintenance, inequality in service or failing to meet the requirements of the community leading to poor adoption. (Barnes and Ashbolt, 2006). On the other hand, decentralized sanitation encompasses a broader variety of systems that share the common trait of managing the wastewater locally. Systems that meet this definition vary in the level of technological sophistication, from low-tech systems such as pit-latrines to high-tech systems such as household-level full treatment units equipped with aerated or anaerobic biological reactors, filters, and disinfectors. Accordingly, environmental, public health and societal benefits of these systems are also highly diverse. Generally, it is understood that decentralised systems allow taking a bottom-up approach to sanitation planning which is more effective for solving specific sanitation problems in a community. (Kalbermatten, 1982)

There are specific strengths to different technologies and approaches. Through a comparative assessment of a set of sanitation system alternatives in terms of their costs and benefits; not only financial but broader economic, environmental, social costs and benefits; most appropriate sanitation interventions for a given place can be identified. Generally, it is understood that centralized approaches are more suitable in densely populated urban area and decentralized solutions are suited for rural areas. But making that distinction in practical applications is not a trivial decision. Fast developing urban and peri-urban areas in developing countries have complex spatial structures, little adherence to spatial planning designations and are overall heterogenous. Therefore, in such settings, sanitation solutions that utilize a combination of different technologies from both centralized and decentralized approaches may provide better public health, environmental and social benefits than any single type of system.

This research is motivated by the need to expand the current theoretical framework and practice of sanitation planning, to include portfolio approaches that consider a wide range of centralised and decentralised technology alternatives and intend to maximise the overall sustainability of sanitation service.

1.1 Research Need

The conventional practice of sanitation planning follows a linear process starting from selection of a project area—usually an administrative area—, then developing alternatives and selection of technology based on a feasibility study. There are several drawbacks in such an approach. Technical and financial feasibility is often prioritised. Conventionally, centralised sewerage is considered the first choice without due consideration for alternatives. Analyses are done at administrative unit level and therefore constrained by abstract boundaries that do not align with the ideal system boundaries that are influenced by many physical and environmental factors. Analyses at admin unit level are not sensitive to the heterogeneity of settlement characteristics present within a unit. As a result, sanitation projects will have limited coverage and unserved pockets within coverage area. Overall, the benefits of sanitation projects would be unequally distributed.

The central research question in this study is whether it is more beneficial to use a mixture of centralised and decentralised sanitation systems, than a single type of system. To answer this, it is necessary to define the overall 'benefit' from a sanitation service and the method of evaluation need to be applicable to different types of systems.

This study is setup to answer this in converse, by finding the optimum sanitation plan for a given scenario. If it is found to be a mixture of centralised and decentralised, it will validate the initial hypothesis that a combined approach is more beneficial.

Further, it is necessary to develop a methodology to optimally locate different sanitation technologies, when using a portfolio approach. Introduction of such a novel planning process to the practitioners is also challenging. Therefore, it also important to develop tools and workflows that can facilitate the adoption.

1.2 Objective of the study

- Enhance the understanding on comparative advantages of a mixed sanitation approach
- Develop a framework for common appraisal of different sanitation alternatives
- Optimizing spatial distribution of sanitation technology alternatives in a combined approach
- Develop tools and workflows for adopting spatially explicit planning of portfolio approaches to sanitation planning practice
- Recommend an optimum mix of sanitation technologies for a study area in Sri Lanka

2 Background

2.1 The challenge of sanitation

Sanitation has been a priority area for development for many decades. Within the Millennium Development Goal (MDG) 7 for environmental sustainability, there was a target for halving the population without access to basic sanitation by 2015. As a result of the efforts towards this target, between 1990 and 2015, 2.1 billion people gained access to *improved* sanitation. The number of people practising open defecation has been reduced by nearly 50% since 1990. But the world had missed the stated target. (United Nations, 2015).

SDGs that succeeded the MDGs establish a more ambitious target of providing universal coverage of *adequate* and *equitable* sanitation by 2030. Therefore, the sanitation challenge remains enormous and surmounting this challenge is made difficult by various reasons because (IWA, 2005):

- Coverage in developing region urban areas is low and even where the coverage is reported to be high, the quality of service is often poor and unequal.
- Serving developing region urban areas is increasingly more challenging because of rapid urbanisation and the pattern of development characterised by unplanned and informal settlements.
- Service gaps are highest in the poorest countries that lack the institutional capacity, financial strength and often the political will to support the massive undertakings necessary.

2.2 Sanitation service levels

Common definitions of sanitation service levels are adopted by the academic and professional community to describe the quality of sanitation service. Mainly, the definitions provided by the WHO/UNICEF Joint Monitoring Program for Water Supply, Sanitation and Hygiene (JMP) are widely adopted. During MDG era, two service levels called *improved* and *unimproved* were defined. In the SDG era, it has been updated to a more comprehensive definition, which referred to as the sanitation service *ladder* described in **Table 2.1**. The *improved* sanitation systems of MDG era are further classified here, based on the types of the systems and whether the facilities are shared between households. Namely, the service levels *safely managed, basic* and *limited* in the present definition constitute the *improved* sanitation systems of the MDG era.

Table 2.1JMP Sanitation service ladder. (Source WHO and UNICEF, 2017)

Service level	Definition
Safely managed	Use of improved facilities that are not shared with other households and where excreta are safely disposed of in situ or transported and treated offsite
Basic	Use of improved facilities that are not shared with other households
Limited	Use of improved facilities shared between two or more households
Unimproved	Use of pit latrines without a slab or platform, hanging latrines or bucket latrines
Open defecation	Disposal of human faeces in fields, forests, bushes, open bodies of water, beaches or other open spaces, or with solid waste
Note: improved facilities include flush/pour flush to piped sewer systems, septic tanks or pit latrines; ventilated improved pit latrines, composting toilets or pit latrines with slabs.	

2.3 Present status

2.3.1 Global outlook

Since adoption of the SDGs 2015, further progress has been made towards achieving sanitation targets. JMP tracks the progress in this regard. **Box 1** contains an excerpt from their reporting on the present status on sanitation in the world. Statistics indicate that despite the remarkable developments, the world is not on track to achieve the declared SDG target of universal coverage by 2030. Confirming this observation, Hutton and Varughese, (2016) report that the capital investments required to achieve the water supply, sanitation, and hygiene SDGs (targets 6.1 and 6.2) amount to about three times the current investment levels.

From 2015 to 2020,

- The proportion of the global population using safely managed services increased from 47 % to 54 %, rural coverage increased from 36 % to 44 %, and urban coverage increased from 57 % to 62 %.
- The population practising open defecation decreased by a third, from 739 million people to 494 million. 85 % of this drop occurred in rural areas.
- The number of countries with estimates available for safely managed services increased from 84 to 120, and the global population with data available increased from 48 % to 81 %.
- On average, use of safely managed services increased by 1.27 percentage points per year (% pts/yr) at the national level, 1.48 % pts/yr in rural areas, and 0.84 % pts/yr in urban areas.
- Achieving universal access to safely managed services by 2030 will require a 4x increase in current rates of progress (15x in LDCs and 9x in fragile contexts).
- At current rates of progress, the world will only reach 67% coverage by 2030, leaving 2.8 billion people without safely managed services.

In 2020,

- 3.6 billion people lacked safely managed services, including 1.9 billion people with basic services, 580 million with limited services, 616 million using unimproved facilities, and 494 million practising open defecation.
- 120 countries and seven out of eight SDG regions had estimates for safely managed services, representing 81% of the global population.
- 62 countries had achieved universal (>99%) access to at least basic services, including eight countries that had achieved universal access to safely managed services.
- Eight countries are on track to reach universal access to safely managed services, and 26 countries are on track to reach universal access to at least basic services between 2020 and 2030.
- Two thirds of people who still lacked even basic services lived in rural areas. Nearly half of them lived in sub-Saharan Africa.
- 92 % of the population practising open defecation lived in rural areas.

Box 2.1 Present status of sanitation, excerpt from Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020, WHO and UNICEF 2021.

2.3.2 Sri Lankan situation

Sri Lanka has made some noteworthy achievements in sanitation development such as the present 94 % coverage of basic or better sanitation resulting from decades of steady growth (**Figure 2.1**) (WHO and UNICEF, 2021). However, the quality of the service is poor in many cases. Sri Lanka does not officially report the coverage of safely managed sanitation. As per information available through the National Water Supply & Drainage Board (NWSDB), Sri Lanka's public sector water utility and authority, population served by sewer systems and Faecal Sludge Management (FSM) schemes that quality for safely managed sanitation is at 2 % and 9 % respectively, indicating that coverage of safely managed sanitation would be about 9 % in 2020 (NWSDB, 2021).

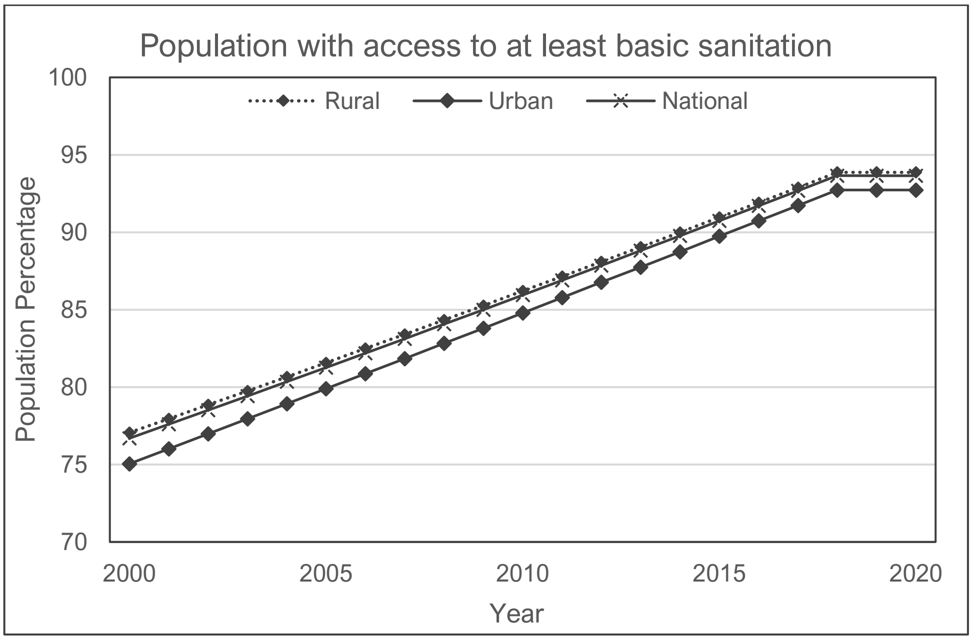


Figure 2.1 Population with access to access to at least basic sanitation. Data source: WHO/UNICEF JMP

A vast majority of Sri Lankans use on-site sanitation systems. Recent surveys have reported that only about 20 % of the on-site systems function satisfactorily (JICA, 2017; NWSDB, 2021). Most people rely on simple pit latrines. Drainage conditions are often poor in most places in the wet zone od Sri Lanka, which encompasses many of the most populous urban regions. Therefore, those are unable to effectively control the environmental pollution. While Sri Lanka has standardized the on-site systems in the SLS745 specifications (Sri Lanka Standards Institution, 2009) presently there is no enforcement for residential systems.

2.4 Sanitation service chain

Sanitation systems can be seen as a chain of sanitation technologies that individually serve a specific role the sanitation value chain. The sanitation value chain is made of a series of links for capturing the wastewater from the sources, storing on-site, transporting to a central facility, treating, disposing safely to environment and reusing the reclaimed water (Bill & Melinda Gates Foundation, 2010). At each link of the value chain, there are numerous sanitation technology alternatives to select from. Available sanitation technologies vary widely in their cost, technological complexity, functional requirements, and their compatibility with other technological alternatives in the service chain. Selection of sanitation technologies should be sensitive to above distinctions and the requirements of the site and the community. Previous researchers have compiled comprehensive databases of sanitation technologies (Spuhler and Roller, 2020; Tilley et al., 2014).

2.5 Centralized vs decentralized sanitation

Different sanitation systems can be broadly categorized as centralized and decentralized sanitation systems. Centralized sanitation systems have the common characteristic of accumulating the wastewater from larger service area to a central point for treatment and disposal. These systems usually comprise a network of sewers pipelines and pumping systems for collecting wastewater and conveying to a centralized treatment system. Some common conveyance systems used in centralized sanitation systems include the conventional gravity sewer networks, vacuum sewer networks and simplified or small-bore sewers. Due to advantages of scale, a wide variety of treatment systems are available for the centralized sanitation systems that are unfeasible or unsuitable for on-site systems. Activated sludge systems, extended aeration systems, attached growth systems and treatment pond systems are some of the common wastewater treatment methods used in centralized systems. Disposal and reuse options for centralized systems are also highly varied.

Decentralized sanitation systems on the other hand, treat, dispose, and reuse wastewater at or close to the source. On-site sanitation systems are a subset of decentralized sanitation systems that manage the wastewater at the source. Apart from on-site systems, sanitation systems that operate on a neighbourhood or community level are also classified as decentralised sanitation systems. Wide variety of treatment technologies available for decentralised sanitation also. A well-known term within decentralized sanitation is Decentralised Wastewater Treatment Systems (DEWATS), an approach to applying decentralized technologies as a sustainable solution to overcome the limitations of centralized and on-site sanitation (Gutterer, 2009).

2.6 Urban vs rural sanitation approaches

In many parts of the world, urban areas have generally seen significantly better developments in wastewater infrastructure than rural areas (Massoud et al., 2009). Centralized collection and treatment systems are an effective solution for sanitation challenges in urban areas. While collection, treatment and disposal are all essential components of a sanitation system, collection usually costs more than 60 percent of the total expenditure in centralized systems, especially when population density in low (Jantrania, 1998). For rural areas with sparsely located settlements and low population densities, decentralized sanitations are generally better suited because they are simpler and cost effective (Butler and MacCormick, 1996; Hedberg, 1999; USEPA, 2005). By making the collection component as simple as possible, more resources could be allocated to necessary collection and treatment components.

Peri-urban areas provide essential services and resources like labour, water resources and waste management services for the cities, but they are often poorly integrated with centralized municipal water supply and sanitation services (Törnqvist et al., 2008). Peri-urban areas which have a combination of urban and rural characteristics may benefit from a mix of centralized and decentralized technologies.

Decentralized sanitation options can include the use of conventional septic tank systems or more advanced compact treatment units that perform a higher degree of treatment. Also, it can include clustered, neighbourhood or community level systems with treatment methods such as pond systems or constructed wetlands (Brix, 1994; USEPA, 2005). Hybrid systems such as a combination of septic tanks, sludge transport with vacuum trucks and centralized sludge treatment can be suitable in some locations. Also, there are number of low-cost alternatives suitable for urban areas such as small-bore systems which may either be connected to a conventional treatment plant or a DEWATS system (Lüthi et al., 2011a).

2.7 Sustainable sanitation

A sanitation system may qualify as sustainable if it aligns with the broader definitions of sustainability in providing its service. While the general definitions of sustainability applies to sanitation systems, various researchers and organizations have developed more specific frameworks for evaluation. As per the Sustainable Sanitation Alliance's (SuSanA) definition they need to be economically viable, socially acceptable, technically and institutionally appropriate and protect the environment and natural resources (SuSanA, 2008). Their framework of assessment considers criteria under the aspects of,

1. Health and hygiene
2. Environment and natural resources
3. Technology and operation
4. Financial and economic and
5. Socio-cultural and economic.

Many other sanitation planning frameworks include comparable assessment criteria (Kvarnström et al., 2004). Triple-S framework developed by IRC is well recognized WASH within community and has a focus of rural sanitation. It recognizes ten building blocks of sustainability (IRC, 2016). FIETS approach developed by the Dutch WASH Alliance recognizes five areas of sustainability, namely financial, institutional, environmental, technical and social (DWA, 2013). Boulenouar et al., (2013) review five sustainability assessment tools in the field of sanitation in terms of applicability, cost, complexity, and scalability. Influence of the well-known triple bottom line framework to sustainability (Elkington, 2018) can be observed in many of the above frameworks and tools.

Such criteria would be helpful for various decision makers in the sphere of sanitation planning such as governments and municipalities, financial organizations investing such projects, sectoral authorities, and utility managers. They would also help answering questions such as which technologies among the available centralized and decentralized options would provide better overall benefits (Lundin et al., 1999); which is the central problem investigated in this research. Some of the common criteria used in sanitation planning are discussed below.

Public health

Safeguarding human health is the prime objective of sanitation. Therefore, sanitation systems need to facilitate good hygiene and minimize the risk of infection as much as possible along all the links of sanitation service chain (UNEP/GPA Coordination Office, 2004). Risks of infection such as pollution of groundwater from pit latrines and leaking sewers need to be minimized. Level of service definitions such as *improved sanitation* and *safe sanitation* can be considered indicators of public health criteria of sustainability of sanitation systems.

Environment

Sanitation systems should manage the waste by minimizing the degradation of recipient environments i.e., water, soil and air. They should also reduce the nuisances of noise and unpleasant sights as much as possible. Beyond minimizing the pollution, sanitation systems and provide environmental benefits by returning nutrients and water to the local environment when they allow reuse and recycling. Aspect of energy is also relevant for assessing the environmental sustainability of sanitation systems. Certain sanitation technologies consume significant amounts of energy and therefore have a significant carbon footprint. Especially, pumping systems and aeration systems are highly energy intensive. Emission of methane from treatment systems is also an important environmental concern (Bousquet et al., 2006).

Economy

Cost of construction and operation of sanitations systems and the capacity and willingness to pay of the consumers are important factors that determine economic sustainability of sanitation systems. Beyond an evaluation of financial viability and economic feasibility, a comprehensive economic evaluation should also consider the diverse externalities and indirect costs and benefits. Environmental benefits such as from recycling, social benefits from improved health and job creation are some such indirect benefits that are often difficult to be quantified with a monetary value. Nonetheless such economic factors may be useful for selecting sanitation system most appropriate for different communities with different requirements (Kalbermatten, 1982).

Socio-cultural appropriateness

Success of a sanitation system depends on people's acceptance and the level of adoption. There can be a lot of dynamic, inter-connected and complex drivers that decide overall socio-cultural sustainability, and these can be generally categorized into cultural acceptance, institutional requirements, and public perceptions on sanitation. Sanitation planning exercises need to be sensitive towards these factors ensure that the proposed systems shall be accepted and effectively used by the people (Holden et al., 2004). Institutional aspects are also important considerations. To reap the maximum benefits of costly investments into sanitation systems, institutions should develop the technical and managerial capacities. When communities are included in governing and operating the sanitation systems they should also be equipped with the necessary skills.

Technical and functional requirements

Technical suitability also needs to be an important criterion in sanitation planning. Selected technologies need to be suitable for the site conditions and requirements of the community and the local environment. It should be able to take in expected levels of pollutant loads and provide a satisfactory level of pollutant removal. Overall, the technologies should be robust and adaptable. Generally, these criteria can be met easier than others because of large number of technology alternatives available (Kvarnström et al., 2004).

2.8 Sanitation Planning

Due to the complex needs of the different segments of the served population, diversity in site conditions and the large number of alternatives available, planning sanitation systems becomes a decision making and optimization challenge.

The lack of supporting research in developing countries leads to selection of inappropriate technology in terms of the local physical conditions, operational capabilities, financial resources and socio-cultural acceptability (Massoud et al., 2009). Effectiveness of decentralized sanitation systems depends not only on technical suitability but also on management and maintenance capabilities (Kalbermatten, 1982). Inadequacies of sanitation planning approaches that does not comprehensively address the needs the community are highlighted by the common phenomenon of poorly functioning, broken down or abandoned sanitation infrastructure in developing regions (Barnes and Ashbolt, 2006). Also, there is an understanding that top-down approaches to planning are less effective for solving sanitation challenges in developing world (Kalbermatten, 1982). Participatory or bottom-up approaches to sanitation planning on the other hand allow sanitation planning to be more sensitive to the complex needs on the community.

Previously discussed sustainability aspects of sanitation are useful for evaluation of sanitation system alternatives. Considering such aspects, many sanitation planning frameworks have been developed and applied.

Sanitation planning frameworks generally attempt to address the needs of the specific area and help support decision making about investments on sanitation improvements (Törnqvist et al., 2008). Available sanitation planning frameworks usually focus on a specific type of location or population groups such as urban, rural, poor or non-poor communities (Kerstens et al., 2016). Community Lead Total Sanitation (CLTS) is a framework targeted towards rural communities (Mehta and Movik, 2010). Similarly, there are other frameworks focusing on urban (Parkinson and Lüthi, 2014) and Peri-urban (Törnqvist et al., 2008) settings.

Available planning frameworks vary in the level of complexity, ranging from simple methodologies such as guiding principles and check lists, like the Sanitation 21-framework (Parkinson and Lüthi, 2014) to more complex ones that use methods such as Material Flow Analysis (MFA) (Meinzinger et al., 2009) or Quantitative Microbial Risk Assessment (Surinkul and Koottatep, 2009). SANEX™ is more complex decision support framework which is suitable for both urban and rural areas. It consists of several steps, including a selection and screening of feasible technologies considering a range of criteria regarding settlement and community characteristics, soil characteristics, quality of water supply and pollution control measures. Application of SANEX™ for small communities has been tested in several developing countries (Loetscher and Keller, 2002). Structured Decision Making (SDM) and Multi Criteria Decision Analysis

(MCDA) also common approaches for decision making while reconciling different and opposing interests. These methods have been adapted for sanitation planning frameworks such as the Community-Led Urban Environmental Sanitation (CLUES), (Lüthi et al., 2011b), City Sanitation Planning (CSP),(GoI, 2008), and Santiago (Spuhler et al., 2020). While more complex frameworks support more comprehensive decision making, they are often time intensive and costly. Therefore, they may not be the most appropriate tools for every planning scenario. On the other hand, the simpler ones may not accurately assess the complex needs and challenges to provide a satisfactory level of understanding that can lead to a good solution.

The reality in most developing countries is that spatial characteristics of settlements are highly heterogenous. Boundaries between urban and rural areas are blurred and often does not align with the administrative boundaries that are usually considered as the basis for sanitation planning. Hence, there is a need for spatially explicit sanitation planning methods that are sensitive to competing development priorities like public health, protection of environment and low-cost.

2.9 Spatial optimization of sanitation plans

Site and community specific criteria that should be considered in sanitation planning often have spatial variations. Therefore, sanitation planning should also be spatially explicit, in order to select the most appropriate solution for each location. Geospatial analysis and visualizations have been incorporated with sanitation planning frameworks by previous researchers (Coutinho-Rodrigues et al., 2011; de Moura and Procopiuck, 2020; Holderness et al., 2016; Kerstens et al., 2016; Pierce, 2014). Coutinho-Rodrigues et al., (2011) used a multicriteria evaluation system to select between four pre-configured sanitation system alternatives. Spatial analysis in their study was carried out at municipal level aggregated data. de Moura and Procopiuck (2020) used spatial correlation and hotspot analysis to identify trends of water supply and sanitation in Parana State, Brazil. Holderness et al., (2016) investigated the use of crowdsourced data for spatially explicit sanitation planning. Kerstens et al., (2016) developed a framework for sanitation planning that follows a population density based method for sanitation system selection.

3 Data and Methods

3.1 Study Area

3.1.1 General characteristics

The study area selected for this research is the Gampaha district of Sri Lanka. It includes some of the major urban areas of country, as it is located next to the Colombo district on the urbanized western region of the country. Some parts of the Gampaha district are therefore included in the western metropolitan region, which is the largest urban agglomeration of the country. Other major towns are primarily located along the two major transport corridors within the district, the Colombo-Kandy highway this the link to the central hill-country and the Colombo-Negombo highway that links the coastal towns north of Colombo and Bandaranaike International Airport. Urban areas are undergoing a rapid growth in extent and population. Gampaha district has experienced the highest net migration among the districts in Sri Lanka during 2001 to 2011 (**Figure 3.1**). Implementing a balanced urban growth has been a challenge. Adherence to physical planning regulations has been poor and as a result the spatial characteristics are highly heterogenous. Gampaha district also includes peri-urban and rural areas. Outside of the major transport corridors, settlement character quickly transforms into rural. Agricultural land—mainly paddy and coconut—are found in these areas.

Administrative Division

Gampaha district is level 2 administrative division in Sri Lanka. It forms the northern part of the Western Province. It is bound by the rivers *Maha Oya* to the north and *Kelani Ganga* to the south. Indian ocean and the Negombo lagoon are to the west and the on eastern side, the Sabaragamuwa Province. Districts in Sri Lanka consist of the level 3 administrative divisions called Divisional Secretariate (DS) Divisions which are further subdivided to Grama Niladari divisions (GND). GND is the smallest administrative unit and also the smallest census unit. **Figure 3.2** shows the Gampaha district and its sub-divisions.

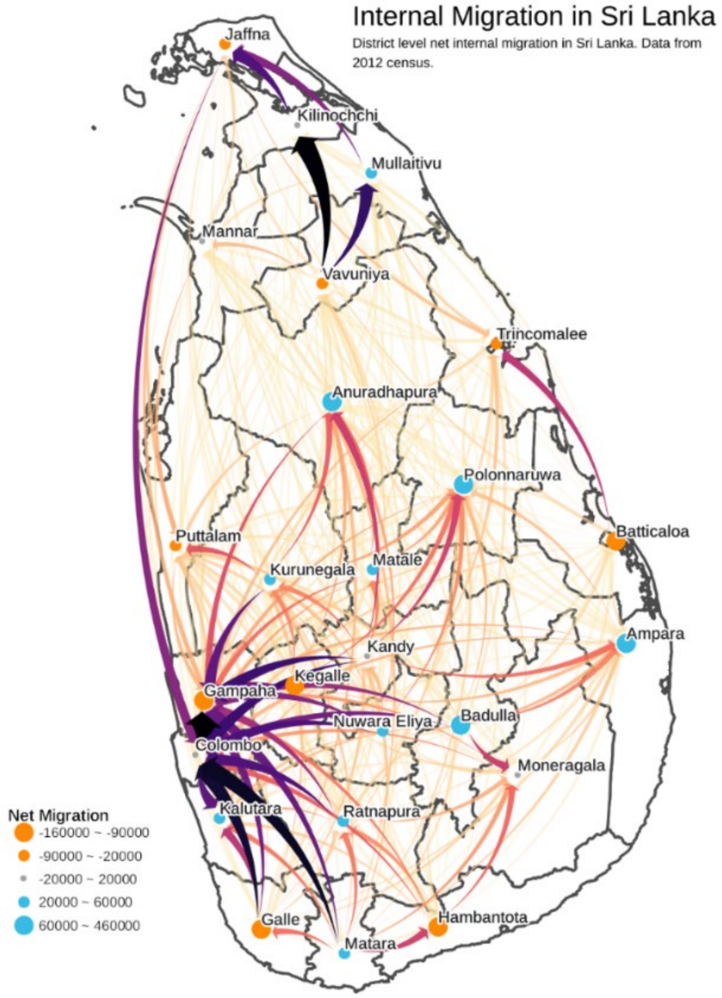


Figure 3.1 Internal migration in Sri Lanka. Data source: Department of census and statistics Sri Lanka.

Figure 3.2 Gampaha District administrative boundaries. Level 3 administrative divisions (Divisional Secretariat Division) are labelled.

3.1.2 Physical and climatological characteristics

Gampaha district is in the wet zone of Sri Lanka and receives an average rainfall of 2014 mm annually. Rainfall is mainly received in the two monsoon seasons May-September Southwest monsoon and the November-February Northeast monsoon. Mean annual temperature 28 °C. It is classified as a tropical rainforest climate (designated Af) in the Köppen-Geiger Climate Classification.

A large part of the Gampaha district is in the coastal plain. Therefore, there are many areas in the western part of the district that are low-lying and prone to flooding. A significant extent of various types of wetlands are present in this area. *Attangalu Oya* is the main river within the district and its watershed covers a large part of the district. **Figure 3.3** shows the important hydrological features of the district.

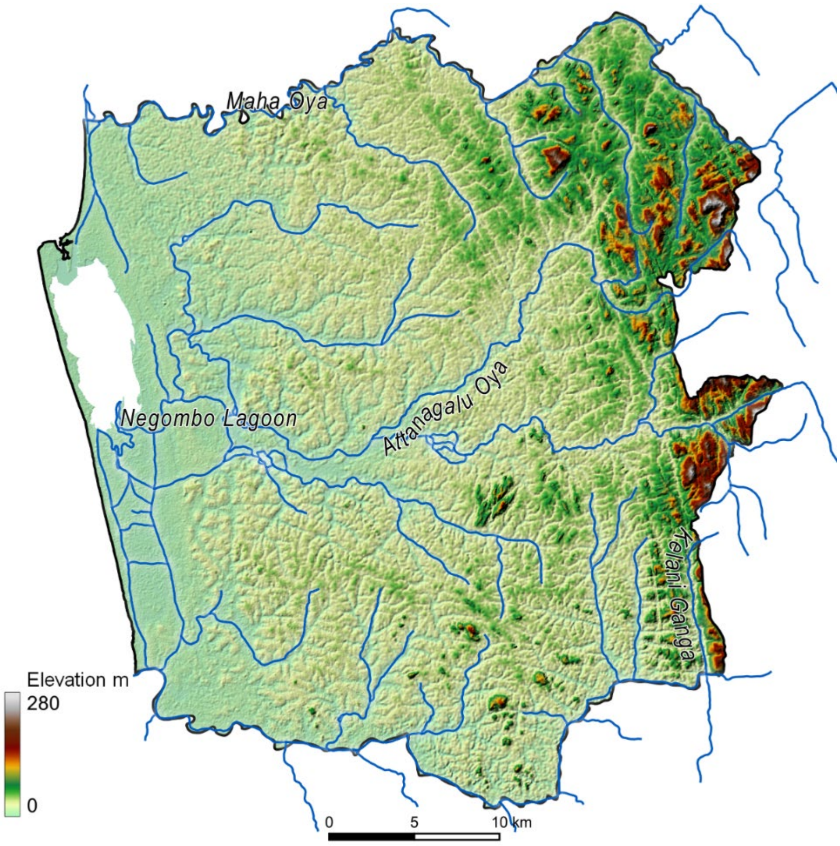


Figure 3.3 Stream network and the elevation of Gampaha district

3.1.3 Demographics

Population of Gampaha district is estimated to be about 2.29 million in 2022 (WFP and UNOCHA, 2016). Gampaha district is the second most populous district in Sri Lanka, trailing behind the 2.30 million population of the Colombo district.

As mentioned above, Gampaha district has seen the largest net migration among all the districts. As shown in the **figure 3.4**, neighbouring Colombo district has both sent and received the largest number of migrants. This may be due the highly urbanized southern parts of Gampaha district being economically connected with the Colombo city. These parts of the Gampaha district are included in the Western Metropolitan Region. The mean household income in Gampaha district was 72,834 LKR (about 56,000 JPY) in 2016 (Department of Census & Statistics, 2017).

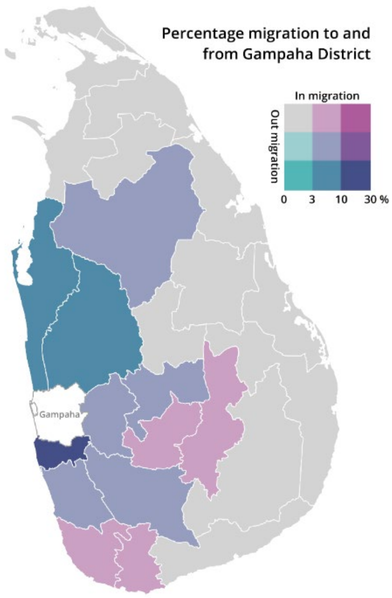


Figure 3.4 Migration between Gampaha district and the neighbouring districts

3.1.4 Status of water supply and sanitation

There are only two municipal sewerage systems in the district, and together they only serve about 16,000 persons. **Table 3.1** presents the statistics for water sources and sanitation methods of the households as per the 2012 census. A vast majority of the households are reported to use on-site sanitation methods such as pit-latrines and septic tanks. Census records indicate that 93% of households use septic tanks. However, subsequent surveys have reported that, most of the on-site systems do not comply with the specifications for septic tanks. A field survey done for preparation of the Sewerage Masterplan of 2017 (JICA, 2017) found that 80 % of the on-site facilities are not standard septic tanks with soakage pits and most only fit the description of collection pits.

Significant environmental problems attributed poor quality of wastewater disposal systems have been reported in the area. Pollution of groundwater indicated by presence of faecal coliform has been reported by researchers and institutions (Gunawardana et al., 2011; Imbulana et al., 2006; NWSDB, 2021).

Table 3.1 Household statistics of water supply and sanitation in Gampaha district

Type of service	Amount	Percentage %
Total Households	604,009	100
Water Supply		
Protected well	361044	59.77
Unprotected well	13,128	2.17
Piped water supply	170762	28.27
Rural water projects	18,388	3.04
Tube well	35,527	5.88
Surface water	274	0.05
Rainwater	131	0.02
Bottled water	605	0.10
Other	4,150	0.69
Sanitation service		
Connected to sewer	24,117	3.99
Water-sealed toilet and septic tank	561,768	93.01
Pour-flush toilet (No water seal)	10,277	1.70
Direct Pit	6,551	1.08
Other	536	0.09
No facility	760	0.13

3.2 Research Outline

To achieve the stated objective of optimizing spatial distribution of sanitation systems, a methodology based on spatial data analysis is developed. A set of sanitation system alternatives are pre-selected considering the present status of sanitation in the study area and the policies and plans in effect. Four alternatives are selected for study.

Description of sanitation system alternatives

1. Conventional centralized sewerage

2. Simplified sewerage

3. On-site sanitation with Faecal Sludge Management (FSM)

4. Improved on-site sanitation

Above alternatives are described in detail in the ensuing sections.

In order to select the optimum system for each location, alternatives need to be evaluated using a common framework. An evaluation framework based on the widely accepted three pillars of sustainability was developed. The alternatives are evaluated in terms six criteria grouped under economic, environmental, and social pillars. Inputs for the evaluation are a diverse collection of data regarding the site and the alternatives.

Once the alternatives are evaluated individually, they are combined to form specific sanitation development scenarios. Scenarios are differentiated by the weightages given to each pillar of sustainability. For each location in study area, the optimum sanitation system under any given scenario is selected as the one with highest aggregate score. **Figure 3.5** summarizes the research outline.

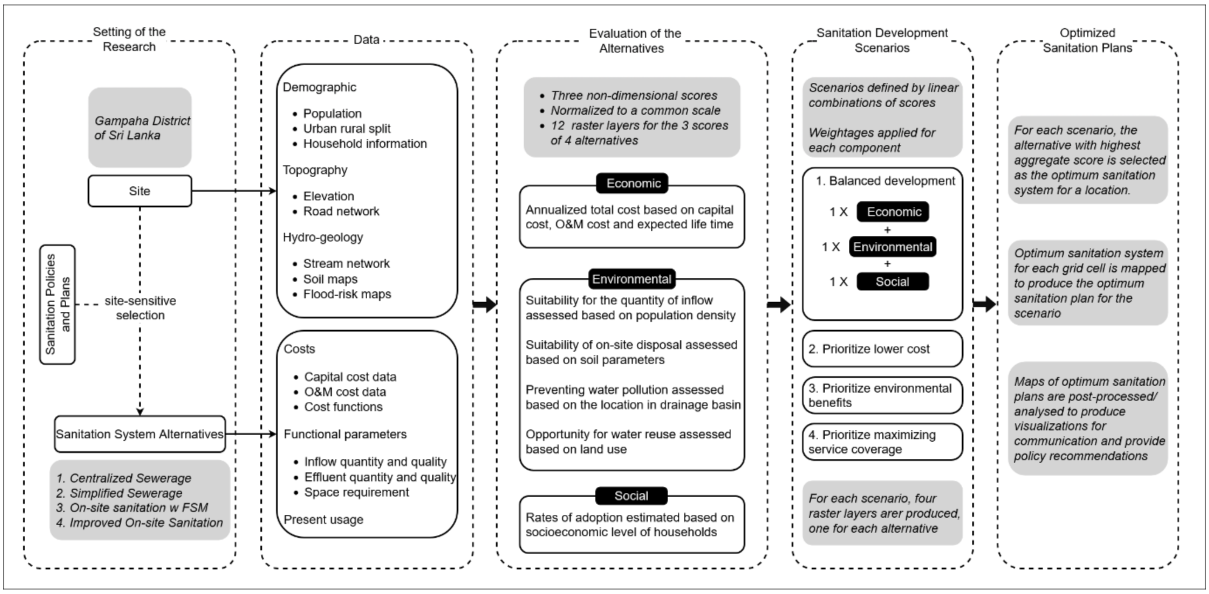


Figure 3.5 Research Outline

3.3 Selection and development of sanitation technology alternatives

A set of sanitation system alternatives were preselected to be used in the spatial optimization exercise. The alternatives were selected based on the following criteria.

Two dimensions were identified in the sanitation technology space. Sanitation technologies vary in the degree of centralisation. There are highly centralised systems such as urban sewer systems, fully decentralised on-site technologies, and a range of technologies in between. Level of technological sophistication is another dimension along which sanitation technologies differ from one another. Even at same level of centralisation there are technology alternatives with different complexity. For example, septic tanks and powered on-site treatment systems like Japanese Jokhosou systems are both fully decentralised but they are vastly different in their technological complexity. **Figure 3.6** visualises some common sanitation technologies with respect to the two dimensions.

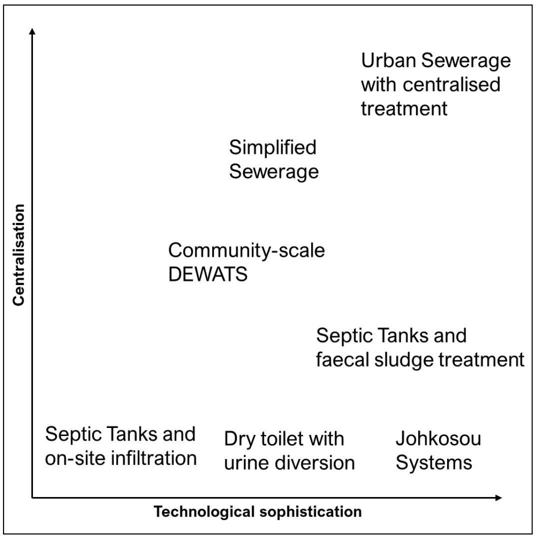


Figure 3.6 Some common sanitation technologies in the centralisation-technological sophistication space

Four technology alternatives were selected, representing different regions of the centralisation-technological sophistication space. In addition, the ability to provide a minimum acceptable level of pollution reduction complying with national discharge standards was also considered. Table X presents the selected alternatives and compares the components of each one at different stages of the service chain.

Table 3.2 Sanitation technology alternatives

	1 Centralized Sewerage	2 Simplified Sewerage	3 Septic Tanks + FSM	4 Improved Septic Tanks
Toilet	Cistern/ Pour Flush toilet	Cistern/ Pour Flush toilet	Cistern/ Pour Flush toilet	Cistern/ Pour Flush toilet
On-site storage & treatment	None	Interceptor tanks	Septic tanks, Soakage Pit/ Infiltration Field	Improved septic tanks7 with anaerobic filtration, disinfection
Collection	Conventional Gravity Sewers	Emptying and transport of intercepted solids with vacuum trucks	Emptying and transport with vacuum trucks	Emptying and transport with vacuum trucks
Centralized Treatment	Biological wastewater treatment	Small to medium wastewater treatment plants, DEWATS systems	Faecal Sludge Treatment	Faecal Sludge Treatment
	Sludge treatment, co-composting, drying	Sludge treatment, co-composting, drying	Sludge treatment, co-composting, drying	Sludge treatment, co-composting, drying
Disposal	Treated effluent to water bodies	Treated effluent to water bodies	On-site disposal by soil infiltration, From FSTP to water bodies	On-site disposal by soil infiltration
	Sludge disposal to landfills	Sludge disposal to landfills	Sludge disposal to landfills	Sludge disposal to landfills
Treated Effluent Quality	BOD5 discharge limit4 is 30 mg/l Typically less than 10 mg/l in present Activated Sludge Plants	BOD5 discharge limit4 is 30 mg/l	30 ~ 50 % BOD reduction6 with septic tanks	BOD5 below 30 mg/l expected
Recycling & reuse	Irrigation, Water Recharge, Application of composed sludge	Irrigation, Water Recharge, Application of composed sludge	Not suitable for local reuse. FSTP effluent reuse possible	Local water reuse - Home gardens

Centralised sewerage was selected as a benchmark alternative that represents the conventional approach to sanitation. A number of centralised sewerage systems have been and are presently being developed in Sri Lanka and it is seen as the standard approach to urban sanitation.

Simplified sewerage alternative was selected because, as a low-cost centralised system that can be implemented at smaller scale, it can be a more appealing choice for low-income urban settings. In simplified sewerage, system components are smaller, and the design tolerances are relaxed. This is justified by using interception chambers at user premises which releases a clarified effluent to the sewers. Therefore, it becomes possible to lay smaller diameter pipes at smaller inclines, i.e. shallow depth, leading to significant cost savings.

Septic tanks and faecal sludge treatment was selected as the third alternative because it represents a direct evolution of the present state of sanitation in this study area. Majority of the people in this area currently use pit latrines and septic tanks. Therefore, upgrading these to standard septic tanks, developing faecal sludge management systems and setting up septic sludge emptying, and transportation systems can be seen as a direct path of progression. The few faecal sludge treatment plants (FSTP) presently being operated in Sri Lanka are small in scale with capacities less than 100 m^3/day (JICA, 2017). Total treatment capacity needed for fully serving Gampaha district with alternative 3 alone, was estimated to be around 3000 m^3/day.

Alternative four was intended to be a high-tech decentralised technology. There are various technologies that satisfy this requirement, such as the Japanese Johkosou systems, on-site biogas generation systems, and anaerobic reactors. NWSDB proposed an improved version of the standard septic tank, by adding anaerobic filtration and disinfection units capable of providing a significantly better treated effluent quality. These systems are expected to reduce Biological Oxygen Demand (BOD) below 30 mg/l. This improved version of standard septic tank, hereafter called Improved Septic Tank, is selected as the fourth alternative.

3.4 Data

In all analyses in this study, the year 2020 was considered as the present. Time varying data such populations, prices, exchange rates and tariffs were also selected from or adjusted for this baseline.

Data sources for different analyses are described in the respective sections below.

3.5 Evaluation of sanitation system alternatives

As reviewed in chapter 2, there are various frameworks for selection of sanitation technologies based their appropriateness to the location and overall sustainability. Among different criteria used for evaluating the sustainability, the influence of the three pillars approach, namely the economic, environmental, and social aspects of sustainability, can be commonly seen. Following this familiar approach, in this study the sustainability of the sanitation technology alternatives was evaluated based on the aspects of environment, economy and society.

3.5.1 Economic assessment of the alternatives

Annual net income from providing sanitation service was considered as the criteria for economic assessment. Net income was calculated based on the costs and revenue of service provision. Sanitation technologies differ widely in their costs and revenues. Further, costs and revenues of a single technology is also non-uniform in spatial distribution.

3.5.1.1 Estimation of cost of Alternative 1: Centralised sewerage

For centralised sewerage, the capital cost is known to vary significantly throughout a service area since the physical components required are vastly different in types and sizes. At the same time, the capital costs for centralised sewerage with its spatial distribution can be estimated with high confidence by following the design and cost estimation process of the professional practise. But the same process cannot be employed in a study like this because, carrying out a complete design in beyond the scope and scale. However, the data inputs for detailed design are available.

Topography and road network data, elevation data and population data are the main inputs for design process and are available for the study area. In addition, the locations of the treatment plants, pump stations and the outfalls are also required to design the sewer network. Considering the data availability, it was decided to use a data-driven prediction model to estimate cost and its spatial distribution.

In this study the centralized sanitation alternative represents a condition where all people in Gampaha district are provided with the services of centralized collection and treatment of wastewater. Collection system is a gravity operated sanitary sewer network, with intermediate pumping stations to control the depth of pipelines and comply with NWSDB design guidelines which specifies a maximum depth of 6.5m for open trench sewer construction.

Treatment is by a set of wastewater treatment plants (WWTP) including existing, planned, and hypothetical facilities. In Gampaha district, currently there are two WWTPs in operation, each with 3000 m^3/day and 7500 m^3/day capacities, with the latter planned to be doubled in capacity by 2025. There are plans for three other WWTPs in the range in 10000 to 20000 m^3/day capacity. In order to define a scenario with a sufficiently high level of centralization, it was assumed that all these plants can be upgraded to a higher capacity. It was estimated that 11 WWTPs with 30,000 m^3/day capacity each will be needed for full-service coverage based on a per capita wastewater generation of 130 l/day and a peak population of 2.42 million. Therefore, in addition to the existing and planned WWTPs, locations for six hypothetical WWTPs were selected, following three main criteria. They need to be close to population centres but outside of central urban areas, have a low elevation and have nearby water bodies suitable for disposal of treated effluent. **Figure 3.7** shows the locations of all existing, planned and hypothetical WWTPs.

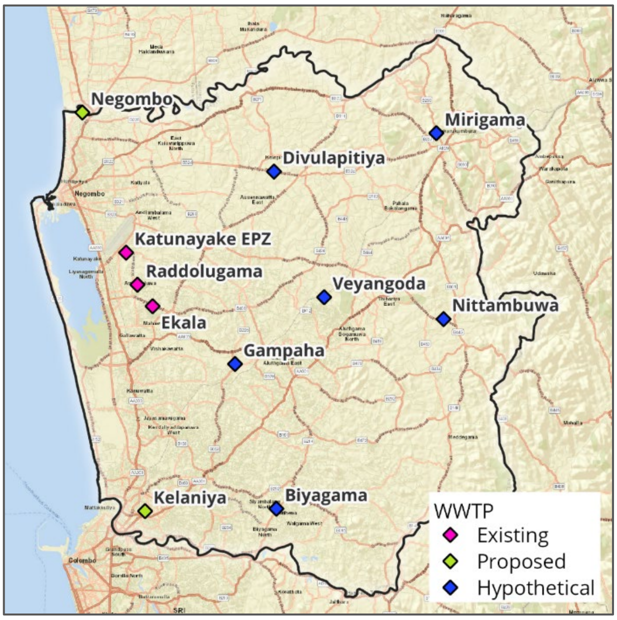


Figure 3.7 Wastewater treatment plants in Gamapaha district. In addition to the existing and pr opposed WWTPs, six hypothetical plant locations are selected to provide complete coverage

Figure 3.7 Wastewater treatment plants in Gamapaha district. In addition to the existing and pr opposed WWTPs, six hypothetical plant locations are selected to provide complete coverage

It was intended to approximate the cost estimated by the detailed design process by using a prediction model trained on same inputs. In the design process practiced by sanitation engineers, data on road network, elevation data, possible locations of main systems components such as WWTPs and pumping stations, and household level populations are taken as main inputs for sewer network geometry design and sizing. After the design, the bill of quantities is prepared based on which the cost can be estimated. This process is highly time consuming and requires expertise in different professional areas. In this study however, cost is the only output of interest as the detailed design and bill of quantities of the system is not needed to be known. Therefore, it was intended to approximate the cost by using an empirical model, based on the same data inputs for the conventional design process.

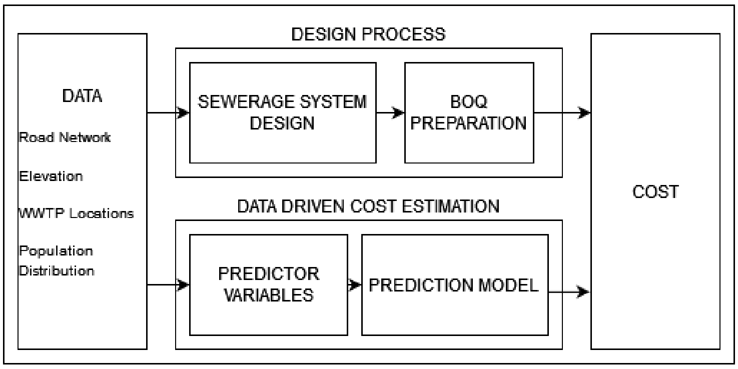


Figure 3.8 Using data-driven cost estimation to approximate the conventional design process

Data variables considered for the prediction model are presented in **Table 3.3**. For estimation of spatial distribution of cost, it necessary to prepare the variables as spatial data, i.e. per pixel averages.

Table 3.3 Data Variables used in the prediction model for the cost of centralised sewerage

Variable	Unit
Target	
Cost	LKR
Predictor	
Elevation above mean sea level	m
Slope	degrees
Distance to nearest road	m
Network distance to nearest PS	m
Network distance to nearest WWTP	m
Population	Count

For building the prediction model, data from a recent sewerage project with comparable characteristics to Gampaha district was required. Ratmalana-Moratuwa is a peri-urban area to the south of the Colombo city and a sewerage system was designed for this area during 2015-2019. Estimated cost of Ratmalana Moratuwa Wastewater

Disposal Project was obtained from NWSDB, the project implementation agency. Geospatial data of the sewer network was also obtained, pipelines as a line segments and manholes as points. Then the costs were assigned to the pipelines and manholes. Finally, a raster layer was prepared at a grid size of 100 m with the cost as pixel value. To ensure accurate assignment of pipeline costs to grid cells, pipelines were split to 10 m segments before rasterizing. The total capital cost includes other cost items with no spatial association such as costs for planning, design, and mobilization. It was decided to distribute all such costs proportionately to the cost of pipe network construction. **Figure 3.9** shows the location of the project and the spatial distribution of in Ratmalana-Moratuwa.

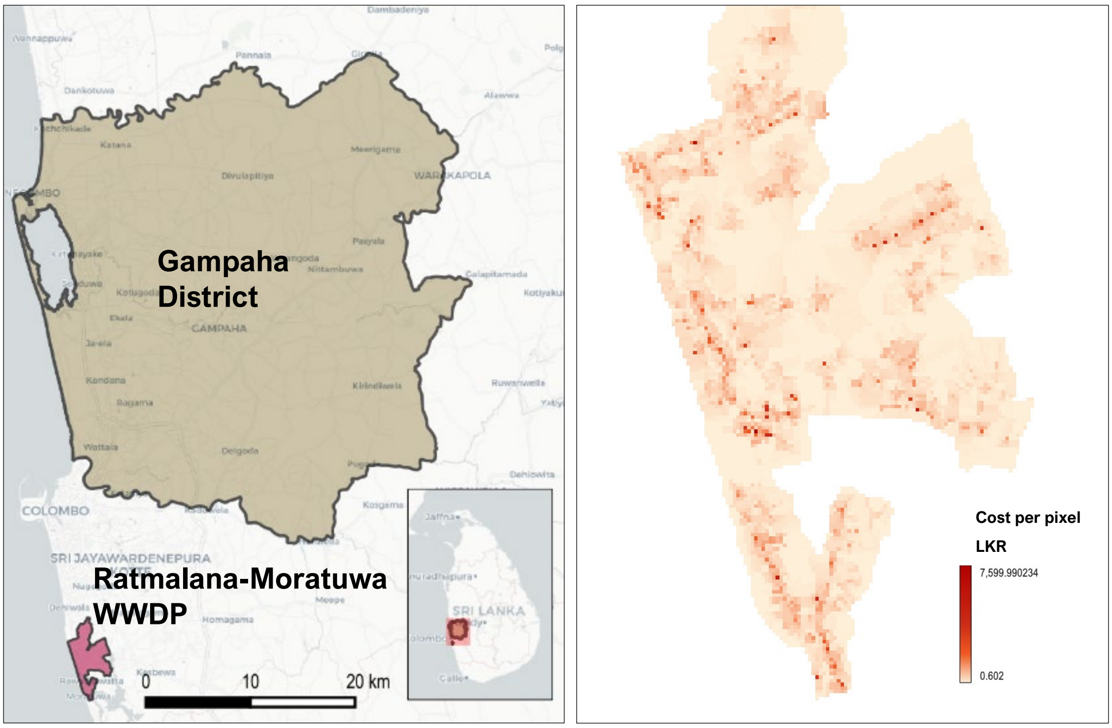


Figure 3.9 Left: Location of Ratmalana Moratuwa Wastewater Disposal Project which is the source of the cost data. Right: Spatial distribution of cost in Ratmalana-Moratuwa project area.

The predictor variable data layers were prepared for both the training area of Ratmalana-Moratuwa and the target area, Gampaha district.

Road network of both areas were extracted from the OpenStreetMap(OpenStreetMap contributors, 2017) . Since OpenStreetMaps is a crowd sourced project, the extracted data were manually inspected and cleaned up by removing roads that are unsuitable for sewer construction, such as expressways, foot paths and private roads. Then for both areas, raster proximity layers were prepared to contain at each grid cell, the Euclidean distance to the nearest road.

As elevation data source for Ratmalana-Moratuwa area, 1 m resolution LiDAR Digital Elevation Model (DEM) with 0.5 m vertical accuracy was obtained from the Survey Department of Sri Lanka. For Gampaha district, the 20 m DEM at 5.81 m accuracy prepared by the VaeSSA project of World Bank and European Space Agency was selected (RSS GmBH, 2019). Both these DEMs were down sampled to a common 100 m resolution using bilinear interpolation.

Slope of terrain was calculated using the above elevation data sources. Average slope in 100 m grid cells was calculated.

High Resolution Settlement Layer (Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, 2016) with year 2015 data was selected as the population data source, because of its superior resolution of 30 m and its strong methodology of assigning populations to built-up areas recognized by image processing on high resolution satellite imagery. Populations were down sampled to 100 m by taking the sum within each grid cell.

Locations of the pump stations (PS) and the wastewater treatment plant (WWTP) of Ratmalana-Moratuwa project were known. For Gampaha district WWTP locations were selected following the criteria described above. Pump Stations in Gampaha district were selected as follows. In Ratmalana Moratuwa Wastewater Disposal Project with generally flat terrain, pump stations are provided at about 5 km distances along a pipeline, to control the depth of sewers above 6.5 m. Following this trend, 40 points randomly generated within the project area with a minimum of 5 km distance between each other, were selected as pump station locations.

Based on the locations of WWTPs and PSs and the road network from the OpenStreetMap, two sets of iso-distance maps showing the network distance (between each grid cell and PS and between grid cell and WWTP), calculated by the Dijkstra's algorithm (Dijkstra, 1959) were prepared. **Figure 3.10** shows the data layers prepared for training area Ratmalana-Moratuwa.

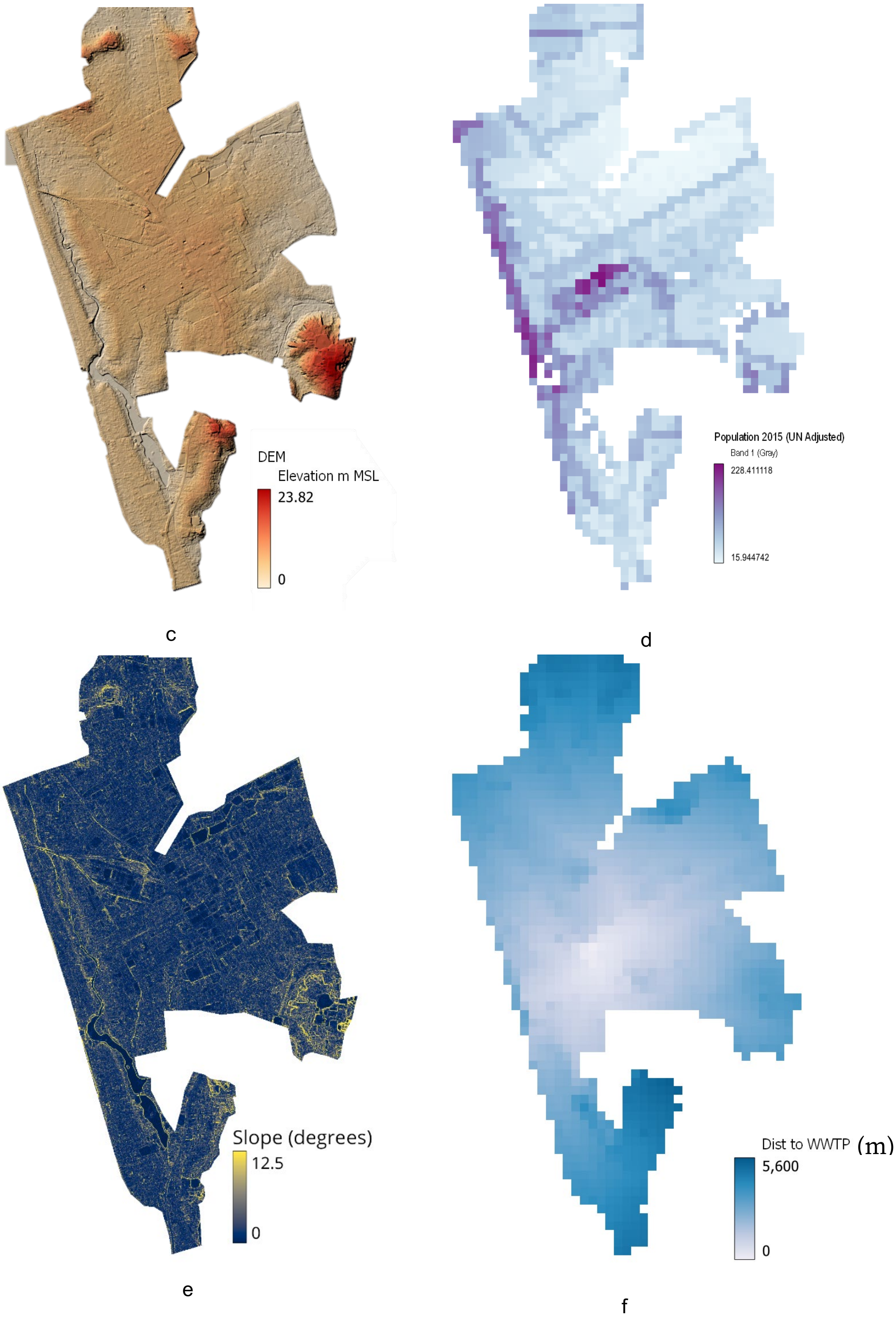


Figure 3.10 Data layers for the predictor variables, in training area (Ratmalana-Moratuwa project) a: Distance to roads calculated based on OSM road layer, b: Network distance to pump stations (PS), c: LiDAR DEM from Survey Dept. of Sri Lanka, d: Slope (degrees), e: Population, f: Network distance to nearest treatment plant (m)

QGIS3 software package, its GRASS, GDAL and SAGA processing packages, and third-party plugins were used in this study. Python and its geospatial libraries like `GDAL` and `rasterio` were also used for analysis and data preparation. R language and its geospatial packages were also used.

Building the prediction model for cost of sewerage

Regression analysis was done with different models to find the relationship between cost and the selected data. First, to examine whether there is a linear relationship, spatial multiple regression was used. Dataset for Ratmalana – Moratuwa area was fitted to the multiple linear regression formula with the cost at each pixel as the independent variable. R^2 was found to be 0.11. Spatial multiple regression tool in QGIS was used in this exercise. Non-linearity confirmed by this result, other different types of models such as linear polynomial models, statistical models, machine learning models and ensemble models. A set of commonly used models that are generally robust in regression were selected. The selected models were trained on the dataset from Ratmalana – Moratuwa. Then accuracy metrics such as Mean Absolute Error and R^2 were calculated between the prediction from the trained model and the actual cost. **Table 3.4** presents the accuracies for the considered regression models. These analyses were done using the `Scikit-learn` machine learning library for python.

Table 3.4 Accuracy in terms of Mean Absolute Error (MAE) and R2 between actual and predicted cost for training dataset with different regression models

Type of Model	Model	MAE (LKR)	R^2
Linear Models	Ridge Regression	96.74	0.31
Linear Models	Polynomial Regression	87.74	0.444
Support Vector Machines	SVM Regression	114.12	-0.025
Nearest Neighbours	KNN Regression	86.47	0.391
Decision Trees	Decision Tree Regressor	81.89	0.155
Neural Networks	MLP Regression	88.78	0.31
Ensemble Methods	Random Forest Regressor	57.83	0.65

Random forest regression which provides the best accuracy was then used for predicting the cost for the target area.

3.5.1.2 Economic evaluation of Alternatives 2, 3 and 4

Spatial distribution of costs and revenues of the alternatives 2,3, and 4 are assumed to be proportionate to the population. Therefore, they were estimated based on the per capita values and the population distribution. Per capita costs were referred from relevant data sources for Sri Lanka or similar settings.

For Alternative 2 Simplified Sewerage, rates for year 2005 were referred from *Rural cost functions for water supply and sanitation* published by (OECD, 2005). The values in euros were inflation-adjusted to 2020, based on historical values of the euro. **Table 3.5** summarizes the data and the calculation.

Table 3.5 Per-capita cost of Alternative 2 Simplified Sewerage

	2005 EUR			2020 EUR		
	Capital Cost	Annual OM Cost	Replacement Cost	Capital Cost	Annual OM Cost	Replacement Cost
5000 persons	3,349,392	37134	167470	4217889	46763	210895
Per Capita	670	7	33	844	9	42

For alternatives 3 and 4, rates estimated in NWSDB's *Sanitation Masterplan 2020-2030* (NWSDB, 2021) were referred. Capital costs in alternative 3 are mostly made up of the costs for Faecal Sludge Treatment Plants (FSTP). In alternative 4, capital investments are for providing improved septic tanks for all households. A cost of 100,000 LKR for a four-person household is considered in the masterplan. Capital costs are converted to an annual cost based on the expected lifetime of the systems. Cost estimation of the alternatives is summarized in the **Table 3.6** below.

Table 3.6 Summary of the cost estimation of the selected sanitation alternatives

Alternative	Total Capital Cost (Mn LKR)	Lifespan (years)	Annualized Capital Cost (Bn LKR)	Annual O&M Cost (Mn LKR)	Total Annual Cost (Mn LKR)	Total annual cost per capita (LKR)
1	450300	40	37762.2	10500	48262	19698.86
2	454771	40	38137.2	27151	65288	26648.03
3	499800	20	50905.7	3248.7	54154	22103.85
4	186261	10	27758.3	3250	31008	12656.45

3.5.2 Environmental assessment of alternatives

Sanitation technologies vary in the level of pollution removal they perform. Across different levels of centralisation, the spatial extent of the pollution also varies. Since the sources, pathways and impacts of environmental pollution are significantly different among the selected alternatives, following approach was taken to develop a method to commonly evaluate them.

First, a broad range of relevant criteria were listed, as shown in **Table 3.7**. It was examined whether each criterion has a spatial variation and whether the spatial variation can be objectively described. Following this method, four criteria with a describable spatial variation were shortlisted.

Table 3.7 Shortlisting the criteria for environmental assessment

Criteria	Has a spatial dimension	Spatial variation can be defined	Evaluation based on	Remarks
Technical feasibility	Criteria for technical feasibility to ensure proper function of the systems to provide a minimum acceptable level of pollution reduction			
Suitable for the quantity of wastewater inflow	Yes	Yes	Population density, Built-up area	Requirements of soil characteristics, ground water depth and drainable area need to be satisfied to ensure proper drainage of effluent. Assume per capita water consumption and wastewater generation is spatially uniform although it’s known to be linked with factors like income level.

Suitable for the characteristics of wastewater inflow	Unclear			Wastewater characteristics can also be spatially varying based presence of specific emitters. Relationships are unclear.
Environmental protection	Criteria relevant to reduction of environmental pollution			
Pollution reduction to water environment	Yes	Yes	Typical effluent quality of the technologies, water bodies and their classification, Water extraction points, Flood risk	Due to infiltration or overflow events, sanitation systems can cause water pollution. Drainage analysis based on topography and flood risk maps can be combined to find locations that are more prone to overflows. Impacts are more critical for water intakes for treatment.
Pollution reduction to soil environment	Yes	Yes	Soil parameters like texture, permeability, and groundwater depth	Due to poor drainage, on-site systems can clog and overflow. Effluent quality can degrade. Soil parameters can describe drainage condition of a site. Depth to groundwater table is also important.
Water reuse potential	Yes	Yes	Land Use	Land use type can explain the demand for reclaimed water. More demand in places where urban farming and landscaping is possible.
Odour and Emissions to air	No			There can be odorous emissions and GHGs like methane. Distribution of odour nuisance is assumed to be linked to overflows. GHG emissions are assumed to be uniform in the considered scale.
Nutrient recycling	No			Opportunity for nutrient recycling in all four selected alternatives is low/ spatially uniform
Energy recovery	No			Opportunity for energy recovery is low in all four selected alternatives

3.5.2.1 Suitability of the population density for the quantity of wastewater inflow

There are upper limits of population density for on-site sanitation systems. Systems that dispose effluents on-site using methods like soakage pits, infiltration beds or infiltration trenches, require drainable land surface area. Required area of land increases with the inflow, which is proportional to the population density. Therefore, by referring to the minimum requirements of land area, an upper limit for population density can be derived. Minimum requirements of space at different flow rates are established in various guidelines and standards. **Table 3.8** is an excerpt from the relevant national standard of Sri Lanka, SLS 745 (Sri Lanka Standards Institution, 2009).

Table 3.8 Minimum required distance between soakage pits. Excerpt from SLS 745 Code of Practice for the Design and Construction of Septic Tanks and Associated Effluent Disposal Systems

Average daily flow (m^3/day)	Minimum distance between soakage pits (m)
< 2	10
2 - 5	15
5 - 10	20
10 - 30	36

Population density has an influence on the function of sewer-based systems (Roux et al., 2011), which has been considered in the economic assessment. Sewer-based systems have economies of density and are usually feasible above 200-300 persons/ hectare in developing countries (UNEP/GPA Coordination Office, 2004). However, for environmental assessment of sewer-based systems, population density is assumed to be irrelevant.

Maximum allowable population for on-site systems were estimated based on the following procedure. Gridded population data were obtained from *High Resolution Settlement Layer (HRSL)* (Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, 2016). Built-up area data were obtained from *Global Manmade Impervious Surface Dataset* (Brown de Colstoun et al., 2017). Both datasets are available at 30 m resolution. Considering a 30 m cell size, an upper limit of population at each cell was estimated.

The two extreme cases shown below in **figure 3.11** were considered. In the sparsest arrangement of soakage pits with only one in each 30 m grid cell, space between two soakage pits is 30 m and the corresponding inflow rate is 22.5 m3/day from **Table 3.9**. In the densest arrangement with 10 m distance between soakage pits, allowable flow rate is 2 m3/day for each, totalling to 18 m3/day within 30 m grid cell. Between these two extremes, a flow rate of 20 m3/day is assumed. Assuming a per capita wastewater generation of 102 l/day, this is equivalent to 196 persons. But this amount should be reduced in proportionate to the built-up area. Therefore, for a built-up area percentage of *m*, the upper limit for population becomes *196(1-m)*.

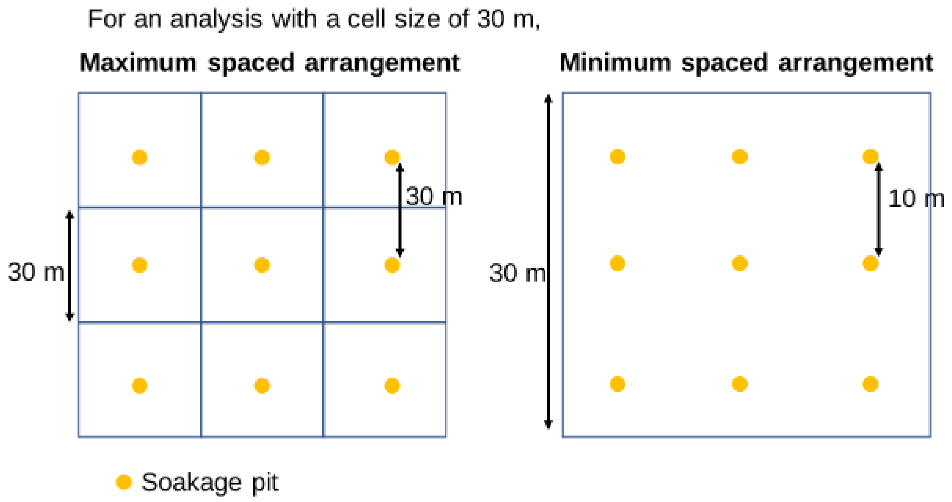
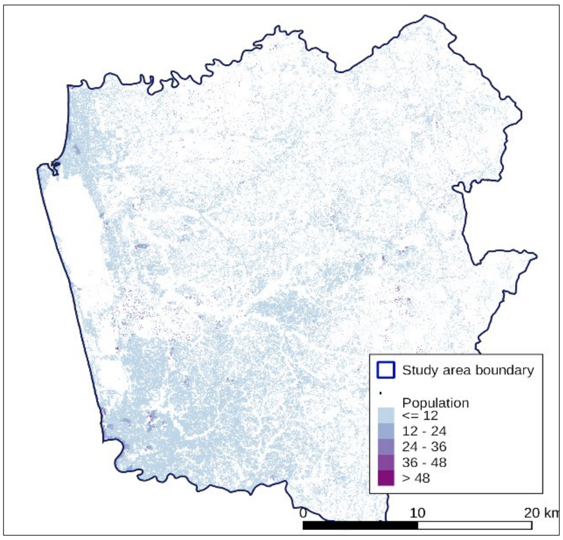


Figure 3.11 Extreme cases of arranging on-site effluent disposal compliant with the national standards

Then using the derived threshold formula, population at each grid cell was rescaled to between 0 and 1, with 0 corresponding to population equal or greater than the threshold value at the cell, and 1 corresponding to population value of 0. In that scale, higher values are more suitable for on-site sanitation. **Figure 3.12** shows the population and impervious surfaces data layers used in the analysis. **Figure 3.13** is a map of the study area showing the index value.



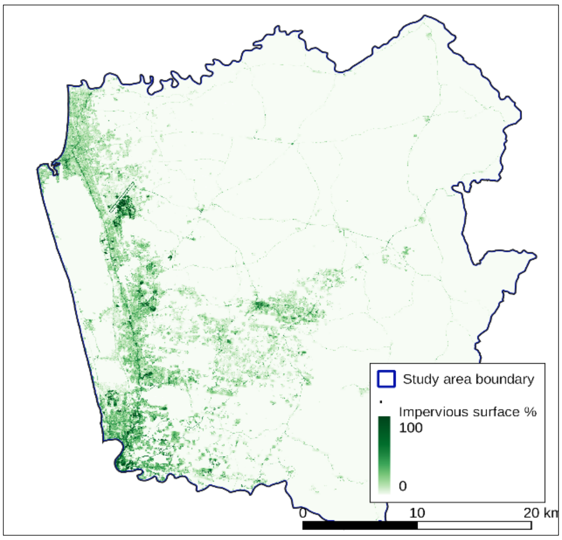


Figure 3.12 Left: Population distribution from High Resolution Settlement Layer (HRSL). Right: Impervious surfaces from the Global Man-made Impervious Surface (GMIS) Dataset

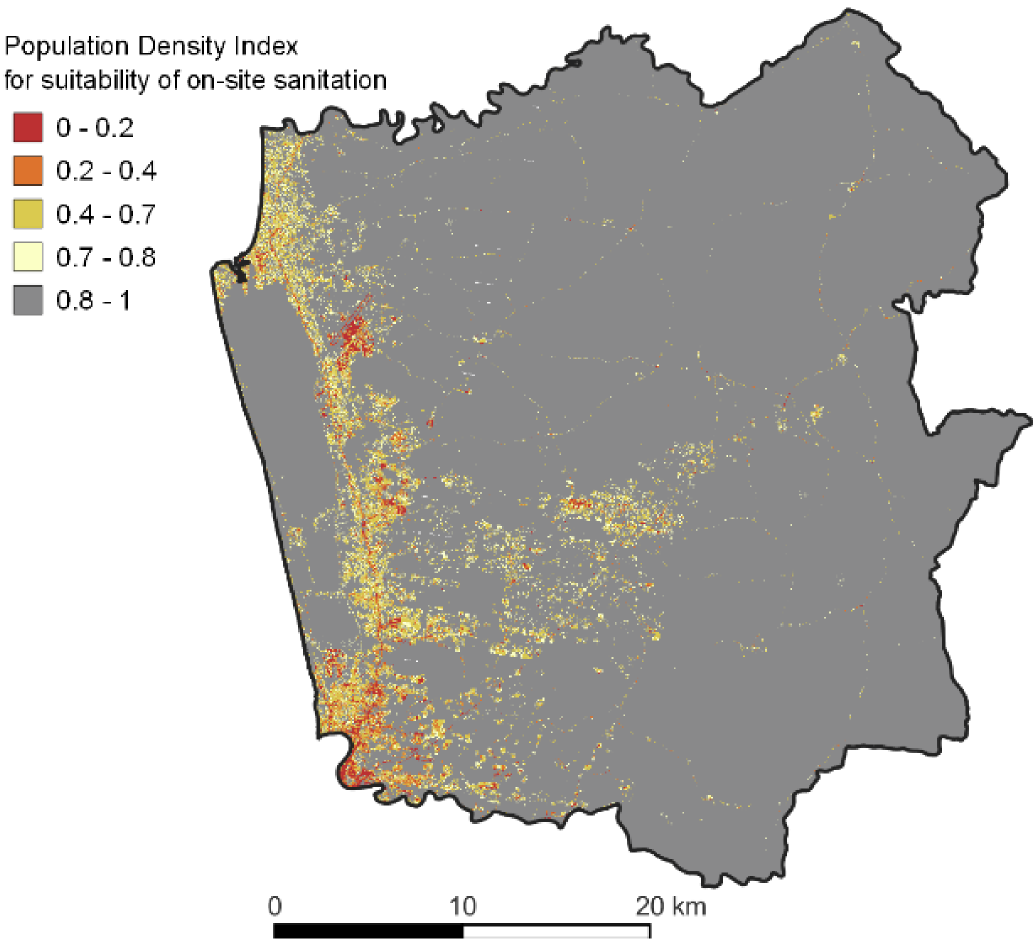


Figure 3.13 Population density index for suitability of on-site sanitation

3.5.2.2 Suitability of soil for on-site disposal

Properties of the soil has an impact on on-site effluent disposal because the permeability of the soil needs to be adequate to drain away the effluent discharge. Sri Lanka's *SLS 745* imposes limits on minimum drainage area based on soil percolation rate. Elsewhere is the world, more comprehensive indicators are used. In many states in the USA, suitability of soils is assessed based on Long-Term Acceptance Rate which accounts for composition, texture, colour, and structure of soil at a site. Soil texture is described by the proportions of sand, silt, and clay present in soil. Generally, when clay content in soils exceeds 35%, the soils are poorly suited for septic systems because of slow permeability. High silt content soils are also unsuitable(Robbins and Ligon, 2014; University of Illinois Extension, n.d.)

A soil suitability index value is developed based on the percentages of the three soil texture components. **Table 3.9** shows the selected desirable ranges which were transformed to an index between 0 to 1, where higher values are better suited for on-site sanitation. Sum of the three components gives an index value between 0 and 3, which is again rescaled to between 0 and 1. The soil texture suitability is mapped in **figure 3.14**.

Table 3.9 Components of soil suitability index

Soil Texture Component	Desirable Range
Silt	Less than 60 %
Sand	40 % – 90 %, higher is better
Clay	Less than 40 %

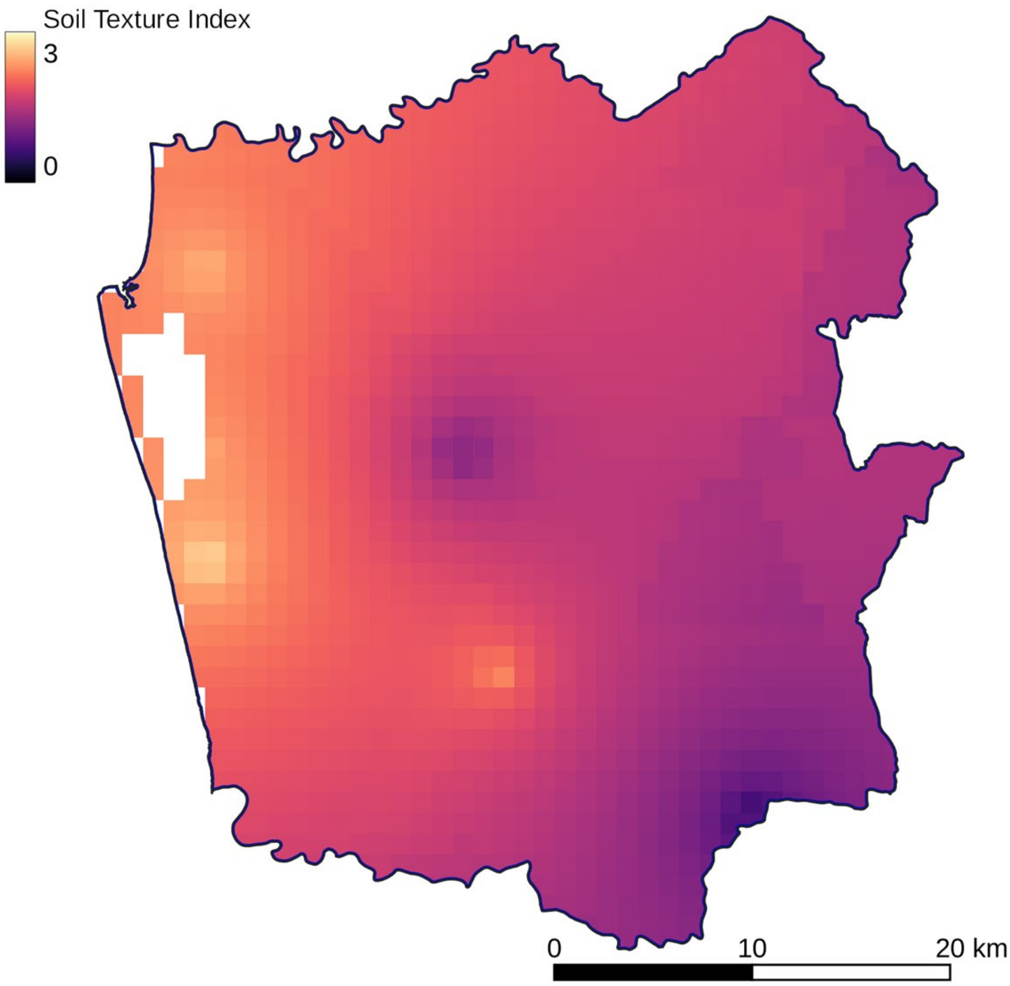


Figure 3.14 Soil texture suitability index

3.5.2.3 Potential for prevention of surface water pollution

Sanitation systems can cause pollution of surface waters via multiple pathways. Incidents of sewer overflows, flooding, and leakages can lead to water pollution. Presence of the water bodies, local hydrology, and hydrogeology influences transport of the pollutants. To collectively represent the potential for surface water pollution through such interrelated sources and pathways, a hydrological model called Height Above the Nearest Drainage (HAND) is used.

HAND is a modified terrain model that gives the height above a nearest drainage, that can be interpreted as a normalization of the surface topography relative to the draining potential and soil water gravitational potential (Nobre et al., 2011). This model has been used as a proxy for several different factors that affect the environmental benefits and issues of the considered sanitation systems. Flooding can affect the function of centralized and decentralized systems alike. Sewer overflows caused by flooding leads to pollution and human health risks. In on-site systems, flooding can not only cause spills and reduce infiltration capacity but also it can damage the systems by septic tank collapse and floatation. Since low laying areas are more prone to flooding, HAND model is suitable in this study as a proxy for flood risk.

HAND model was derived using the VaeSSA DEM (RSS GmBH, 2019) which gives elevations at 20 m resolution. Starting from the DEM, the area was delineated to sub-catchments and the stream network was traced. Within each sub-catchment, height difference between the outlet and each grid cell was calculated. **Figure 3.15** shows the (unscaled) HAND model for Gampaha district. Final HAND model is rescaled to between 0 and 1 for use in subsequent analysis.

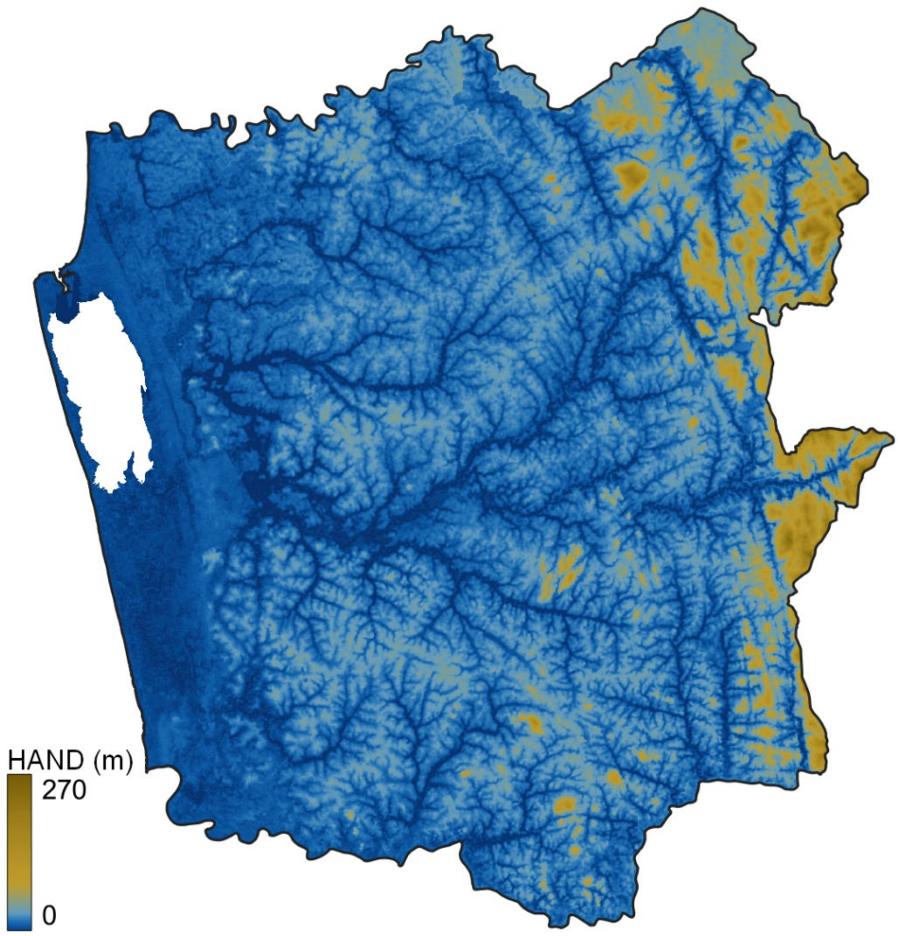


Figure 3.15 Height above nearest drainage (HAND) model for Gampaha district

3.5.2.4 Water reuse potential based on land use

Potential for water reuse has been mapped based on the land use. Two main criteria, namely the need for reclaimed water and the ease of connecting water demand to the treatment facilities were considered in evaluating the different land use categories. **Table 3.10** presents the evaluation scheme. Ratings were given based on a review of the evidence for reclaimed water use in the different land use types. Map of the original land use types are shown in **figure 3.16**. Map of water reuse potential generated by applying the evaluation scheme is presented in **figure 3.17**.

Table 3.10 Land Use types and their relative water reuse potential. 0: No demand, 1: Low, 2: Moderate, 3: High

Land Use	Demand for reclaimed water	Opportunity for adoption	Remarks	Water reuse potential
Bare area	None	None	No demand	0
Mangroves	None	None	No demand	0
Marsh	Low	Medium	Limited demand for water recharge. Adoption is difficult	0.5
Wetland	Low	Medium	Limited demand for water recharge. Adoption is difficult	0.5
Coconut/ Palm tree dominated	High	High	Demand for irrigation and water recharge purposes. Adoption is easy as treated effluent can be applied in the local area through simple conveyance methods	1
Paddy	Low	Low	Demand is low as paddy fields in wet zone are continuously irrigated with canal system with no shortage of water.	0.33
Rubber	Low	None	Rubber crops are generally not irrigated. Plantations have no infrastructure to receive reclaimed water.	0.167
Dense Forest	None	None	No demand	0
Forest Plantation	Low	Low	Limited demand	0.33
Open Forest	None	None	No demand	0
Grassland	Medium	High	Demand for watering grass fields. Easier adaptation as closer to points of generation.	0.833
Scrubland	None	None	No demand	0
Built up area	Low	Low	Limited demand for purposes like urban farming and washing. Adoption requires new infrastructure.	0.33

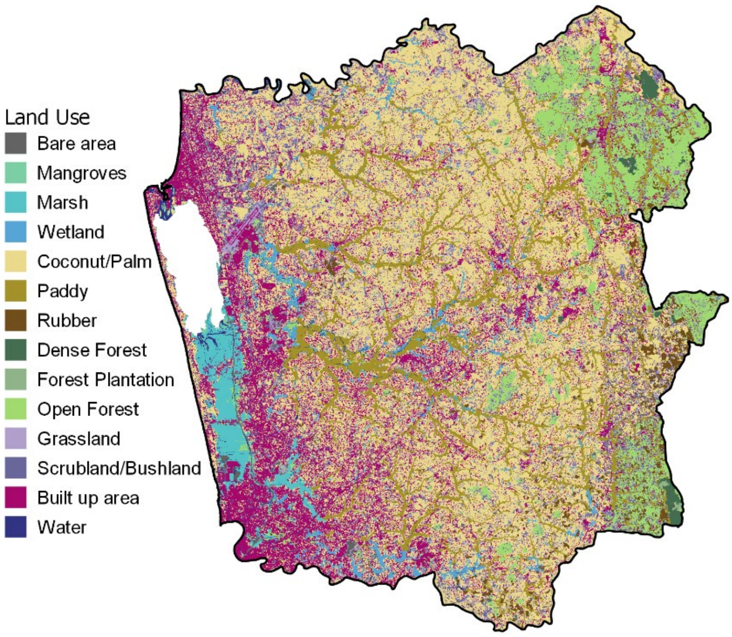


Figure 3.16 Land use types in Gampaha district

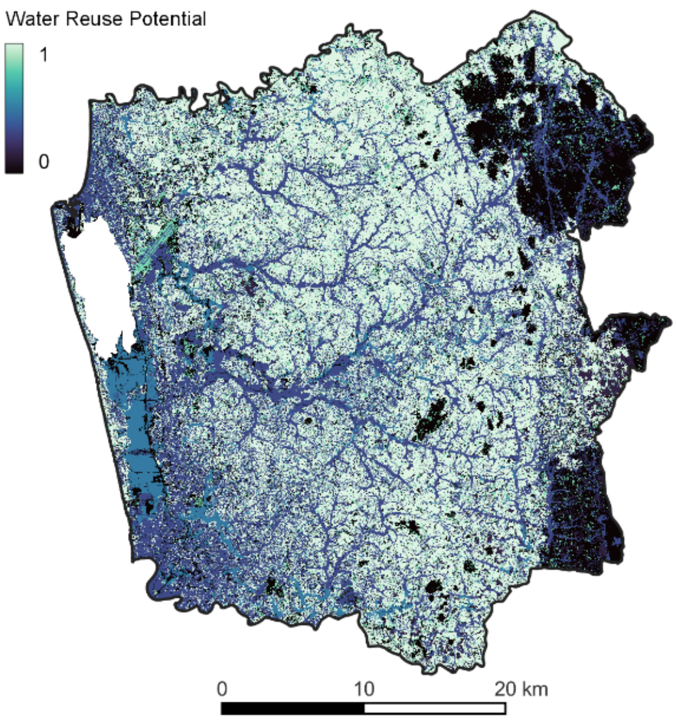


Figure 3.17 Water reuse potential based on land use types

3.5.2.5 Compilation of the environmental score

Some of the above described four indices are not relevant for certain sanitation technology alternatives. Therefore, the indices are modified with appropriate multipliers for the selected sanitation system alternatives, as presented in **table 3.11**. Sewer based alternatives (No.1 and 2) do not have population density limits. Therefore, population density index for these alternatives is a spatially uniform value of 1 (denoted as U1). Both on-site alternatives are given a multiplier of 1, i.e., the base index is unmodified. Soil index too is irrelevant for sewer-based alternatives, hence the U1 modifier. For alternative 3 soil index is given a 0.5 modifier because the conventional septic tanks offer less pollution removal than the improved septic tanks in alternative 4, and therefore infiltration requirements are more critical. HAND model values are unmodified for alternatives 1 and 4, assuming both are affected similarly. Compared to centralized sewerage, simplified sewerage systems are more susceptible to flood hazard because the sewer pipes and manholes are smaller. Alternative 2 is therefore applied a modifier of 0.5. Similarly, Conventional septic tanks are more susceptible to flood damage than Improved septic tanks and are therefore given a modifier of 0.5. For land use based water reuse potential index, Alternatives 1 was given a distance-based modifier (Denoted as D). While centralized treatment can generate the highest amount of reclaimed water, opportunity for local reuse is diminished. Therefore, the index values are modified based on the distance to the nearest treatment plant. Alternative 2 is defined by a higher number of smaller capacity treatment plants and DEWATS systems, with which local reuse is assumed to be possible and therefore assigned a 0.5 multiplier. Conventional septic tanks in alternative 3 do not facilitate water reuse as the effluent quality in inadequate. But the improved septic tanks in Alternative 4, with its anaerobic filtration and disinfection steps, provides water suitable for reuse. Therefore alternative 4 is unmodified. **Table 3.11** summarizes the modifiers for all alternatives.

Table 3.11 Modifiers for the environmental evaluation indices for the considered alternatives. U1: Uniform value of 1, D: Distance based modifier.

Index	Alternative			
	1	2	3	4
Population density index	U1	U1	1	1
Soil suitability index	U1	U1	0.5	1
HAND	1	0.5	0.5	1
LU based water reuse potential index	D	0.5	0	1

3.5.3 Social Assessment of alternatives

A high level of service adoption is necessary for sanitation programmes to be successful in delivering the intended public health and environmental outcomes. Many socio-economic factors of a population affect the rate of service adoptions. Cultural and community acceptance and the capacity and willingness to pay are important underlying factors. Present state of household sanitation facilities, water supply, unit types and income are found to be related to the sanitation system adoption (Okurut et al., 2015). The four selected system alternatives in this study are understood to have different levels of adoption rates linked to the socio-economic status of the households. Supported by available literature (Moseti et al., 2009; Mulatya et al., 2021) on choice of sanitation system and willingness to pay, and the data on costs for households for adopting the technology, the four alternatives were ranked in the order of least to highest expected rate of adoption considering the cost and the maintenance requirements.

Table 3.12 Ranking sanitation alternatives in the order of expected rate of adoption

Rank	Alternative	Approx. cost for households to adopt (LKR)	Maintenance requirements
1	3 On-site Sanitation and FSM	50000	Infrequent, cheaper, and low in technical expertise. Eg: Regular desludging
2	2 Simplified Sewerage	100000	Frequent, cheaper, and low in technical expertise. Eg: Pipe blockages are expected because small-bore pipes are laid at gentler slopes. But at low depth and with interception chambers, maintenance is easy
3	4 Improved Septic Tanks	150000	Infrequent, cheaper, and low in technical expertise. Eg: Restocking chlorine pellets, desludging
4	1 Centralized Sewerage	250000	Infrequent. Costly and high technical expertise. Eg: Maintenance on house plumbing and street sewer connections

The approach for mapping the socioeconomic appropriateness of the sanitation alternatives is first mapping the socioeconomic status and then scaling the results for each alternative based on the above ranking.

Maps of income, socioeconomic level or poverty were not available with sufficient levels of detail. While there are several poverty maps developed for Sri Lanka (Amarasinghe et al., 2005; Chandrasiri and Samarakoon, 2008) including the official poverty map of the department of census and statistics, (World Bank, 2005) their unit of analysis has been the Divisional Secretariat Division (Level 3 Administrative Unit) and therefore would not be suitable for a high resolution spatial analysis.

An exercise of mapping the socioeconomic level was therefore undertaken. Examination of literature revealed that in the absence of actual household income-expenditure data, a set of other descriptive parameters can be synthesized to a proxy socioeconomic index. Vyas and Kumaranayake, (2006) developed a socioeconomic index based on housing unit features, water supply, sanitation, and household amenities by applying principal component analysis (PCA). Referring the above, Dias *et al.*, (2020) developed a socioeconomic index for Sri Lanka which is calculated based on data from the census of 2012 (Department of Census & Statistics, 2012). Their index was reproduced for the Gampaha district, for use in this study. The Index was developed at the scale of smallest census unit of *Grama Niladari* Division (GND) which is the level 4 administrative division in Sri Lanka. **Figure 3.18** shows the socioeconomic index for Gampaha district. Higher values indicate a higher socio-economic level.

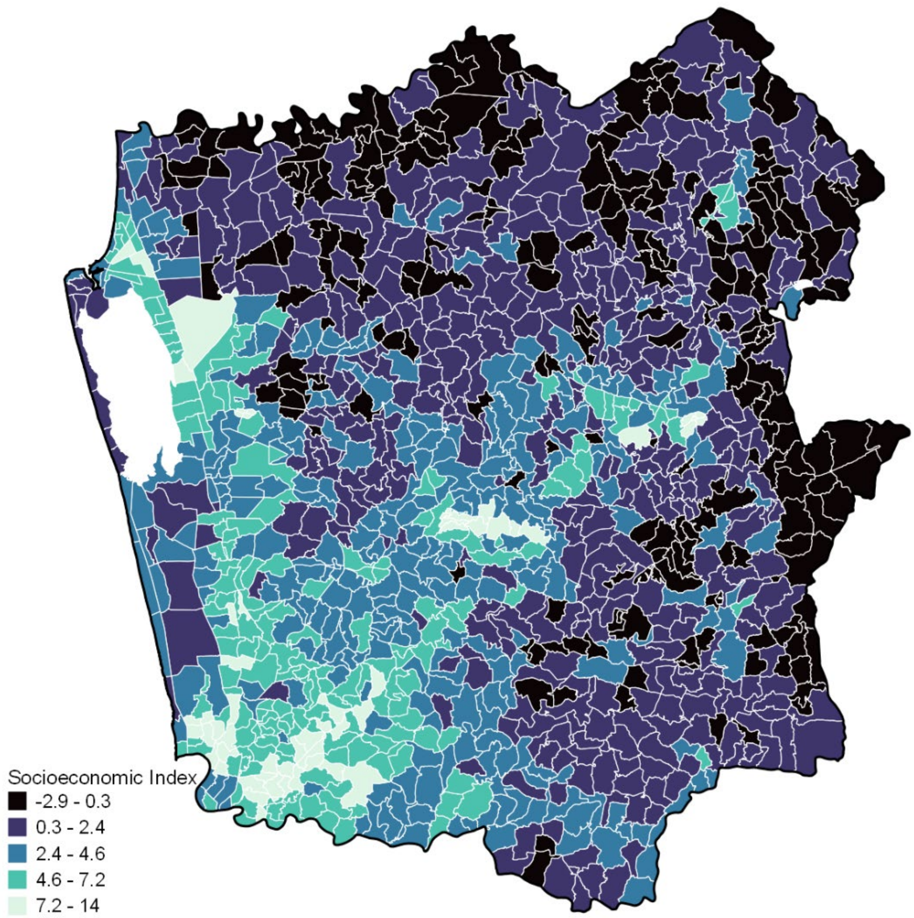


Figure 3.18 Socioeconomic Index for Gampaha District, calculated at the scale of admin division level 4

3.6 Sanitation Development Scenarios

Sanitation development scenarios are formulated to compare optimised sanitation plans under different development priorities. Scenarios are developed by combining the economic, environmental, and social indices of each alternative. Weightages are applied to each index to build different scenarios. First, each index is rescaled to same range (0-255). In the case of economic index, while the cell values have a very high dynamic range, majority is concentrated on a narrow range (See histogram of the cost distribution of Alternative 1 in **Figure 3.19**). Therefore, logarithms of cost values are calculated first, which are then linearly rescaled between 0 to 255. Environmental and social indices are directly rescaled.

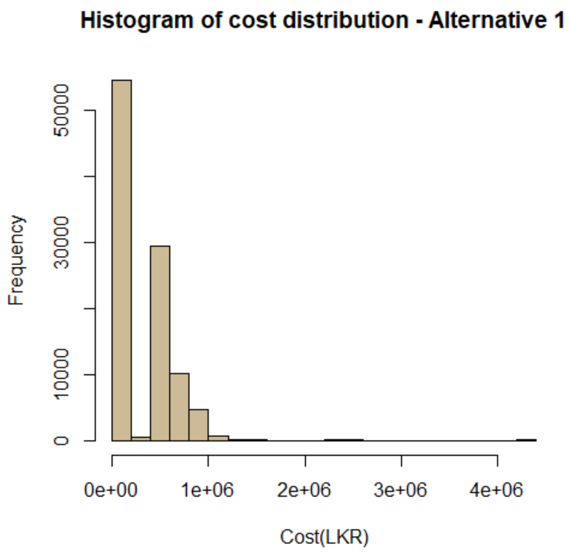


Figure 3.19 Histogram of the cost distribution of Alternative 1

As examples, four scenarios are considered, defined by the weightages presented in **Table 3.13**. They include three scenarios that prioritize each one of the three aspects of sustainability, in addition to a balanced scenario.

Table 3.13 examples of constructing sanitation development scenarios defined by the weightages

Scenario	Economic Score	Environmental Score	Social Score
Balanced	10	10	10
Prioritise low cost	10	0	0
Prioritise environmental benefits	0	10	0
Prioritise maximizing service coverage	0	0	10

3.7 Optimised sanitation plans

Under different sanitation development scenarios, optimum sanitation plans are prepared based on the following definitions.

P_{ecn}. P_{env}, P_{soc} are respectively the economic, environmental, and social scores of an alternative.

W_{ecn}, W_{env}, W_{soc} are respectively the weightages for economic, environmental, and social scores that defines a scenario.

For alternative i, from a set of n alternatives,

the grid of the overall sustainability score of alternative i under scenario (W_{ecn}, W_{env}, W_{soc}),

$$S_i = W_{ecn}P_{ecn} + W_{env}P_{env} + W_{soc}P_{soc}$$

In the optimum sanitation technology grid A for the scenario,

$$\text{Grid-cell } a_{j,k} = \max_{i \in n}(S_{i_{j,k}})$$

All evaluation indices, P_{ecn}. P_{env}, P_{soc} are prepared as georeferenced raster grids with the same grid size and alignment. Linear combinations of the raster layers can be calculated programmatically or by using GIS applications. For each scenario, linear combinations of individual raster layers with above weightages applied are produced for each sanitation alternative. Then for each cell, the alternative giving the highest score was selected as the appropriate sanitation system for the individual cell. Mapping the best choice of sanitation technology alternative of all cells, produces the optimised sanitation plan for the study area, under the considered scenario.

3.8 Interactive sanitation scenario explorer

By following the above-described method, a large number of unique sanitation development scenarios can be produced as combinations with different weightages applied to economic, environmental and social scores. To facilitate exploration and comparison of different scenarios for intended users without skills in GIS for programming, a user-friendly interactive scenario explorer was developed. Software was written in python, and it was hosted online as a webapp at the URL https://share.streamlit.io/vajiral/utr-app/main/scnapp_strlt.py. Code is available at https://github.com/VajiraL/utr-app.

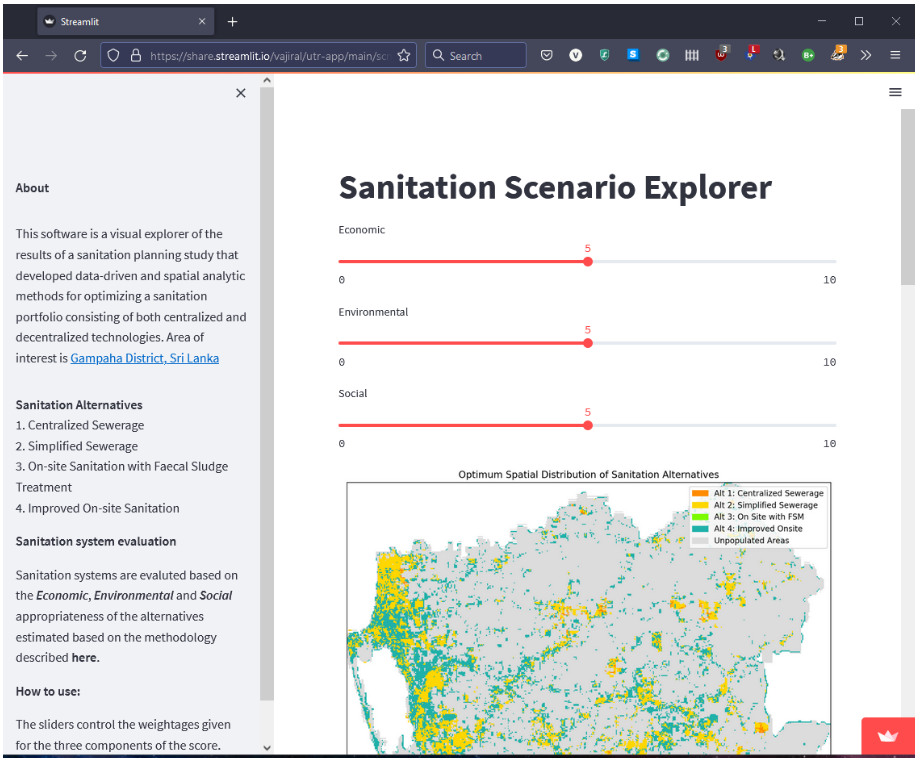


Figure 3.20 A screenshot of the Sanitation Scenario Explorer

4 Results and Discussion

4.1 Spatial distribution of the cost of sewerage

A data driven cost estimated model was developed as a part of this this study to approximate the output of the conventional design-BOQ-costing workflow

First, a linear multiple regression model fitted to the prepared dataset for the training area. It was found to give poor fit with R^2 at 0.11 suggesting that there is no linear relationship between the selected variables and the cost. Other linear models like ridge regression and polynomial regression also failed to discover a strong relationship, although the model fit was significantly higher (**Table 3.4**). Since the selected data are derived from the main the inputs that go into the design of sewer systems, it is assumed there is some other kind of non-linear relationship. Machine learning models may be suitable for uncovering such complex relationships. Different machine learning models tried in this study showed varying levels of accuracy. Support Vector Machines showed uniquely worse results. Random forest regression provided the best fit at 0.65 which was deemed acceptable for purpose of this study. Random forest models build a multitude of decision trees from training data connecting predictor variables to the predicted. When used for regression as in this study, their output is the mean of the prediction of all individual trees. Due to its nature, random forest models can be seen as a *black box* type model. However, it is also a robust model that provides good accuracy with less susceptibility for over-fitting to the training data. In this study where relationships between variables are known be varying at different places, it is reasonable that random forest provides better results than a model with a more explainable mechanism.

Predicted cost from random forest model is visualized in **figure 4.1**. By visual observation reveals that the different levels of population density have been successfully differentiated. Higher cost regions are centred around the WWTPs. This can be explained by fact that pipelines will converge towards the WWTPs and as the wastewater flows accumulate, pipe sizes will need to increase.

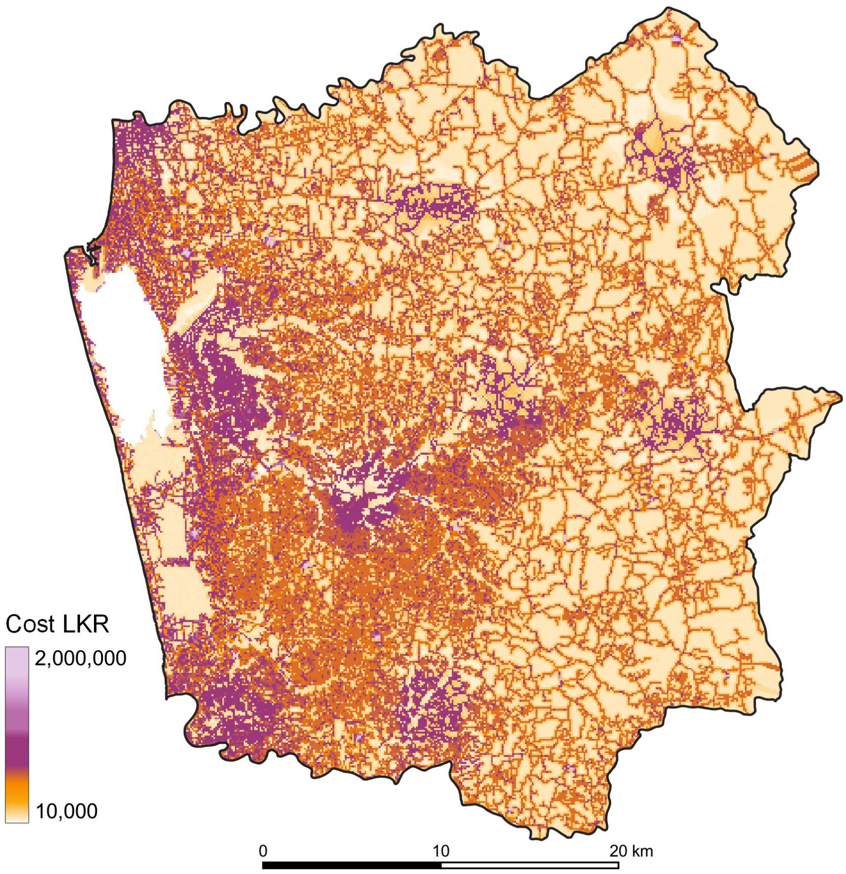


Figure 4.1 Spatial distribution of the cost of centralised sewerage as predicted by the random forest model

WASH SDG Costing Tool is a sector financing tool created by UNICEF. This tool can be used for country level financial analysis for water and sanitation investments towards SDG achievement. **Table 4.1** presents a comparison between the costs estimated by this study and the *WASH SDG Costing Tool.* Actual cost is nearly twice the amount estimated by the *WASH SDG Costing Tool,* and this trend has been retained in the predicted result.

Table 4.1 Comparison of cost estimated in this study with WASH SGD Costing Tool

	Training Area	Target Area
Present study	Actual 7.8 billion LKR	Predicted 456 billion LKR
WASH SDG Costing Tool	Estimate 4.4 billion LKR	Estimate 226 billion LKR
Ratio	1.8	2.0

Model verification should be done by applying for another area where actual cost data is available. At present such data could not be obtained. However, there are several sewerage projects being planned within this area and once cost estimates from these projects become available, they can be used to verify the prediction model.

4.2 Economic assessment of the sanitation technology alternatives

Cost distributions for the four alternatives are mapped in the **figure 4.2**. In the alternatives 2,3 and 4, the spatial pattern of cost follows population as they were estimated based on per capita cost. Centralized sanitation in alternative 1 has a distinct pattern. There the costs are aggregated mainly around the road network. This is consistent with the real-life conditions as largest costs in a sewerage system are often on pipe-laying along the roads. The influence of population density is also visible.

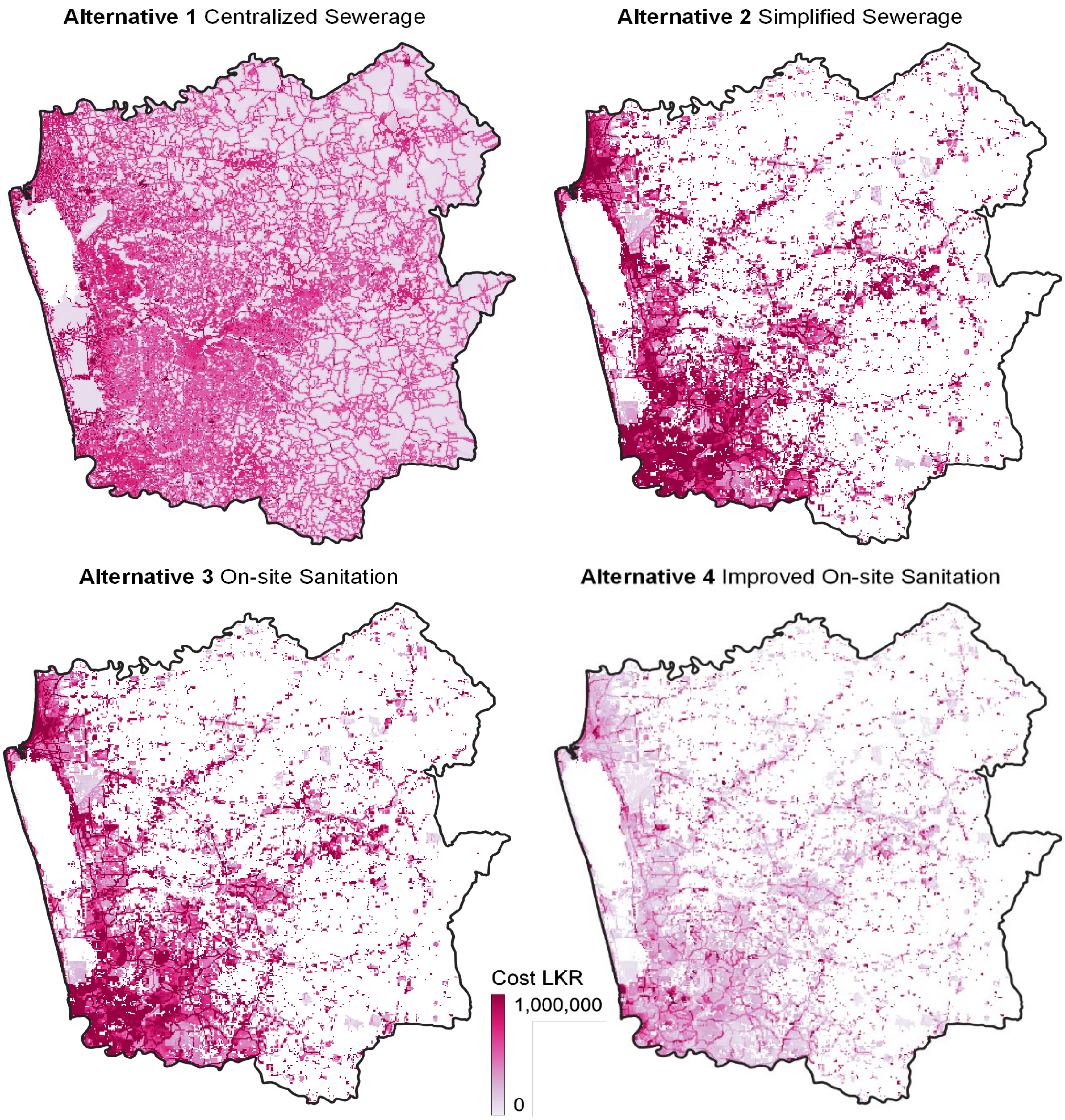


Figure 4.2 Results of economic assessment as the cost of each alternative

4.3 Environmental Assessment of the sanitation technology alternatives

Environmental scores of the four alternatives prepared by combining the modified evaluation raster layers are presented in **figure 4.3.**

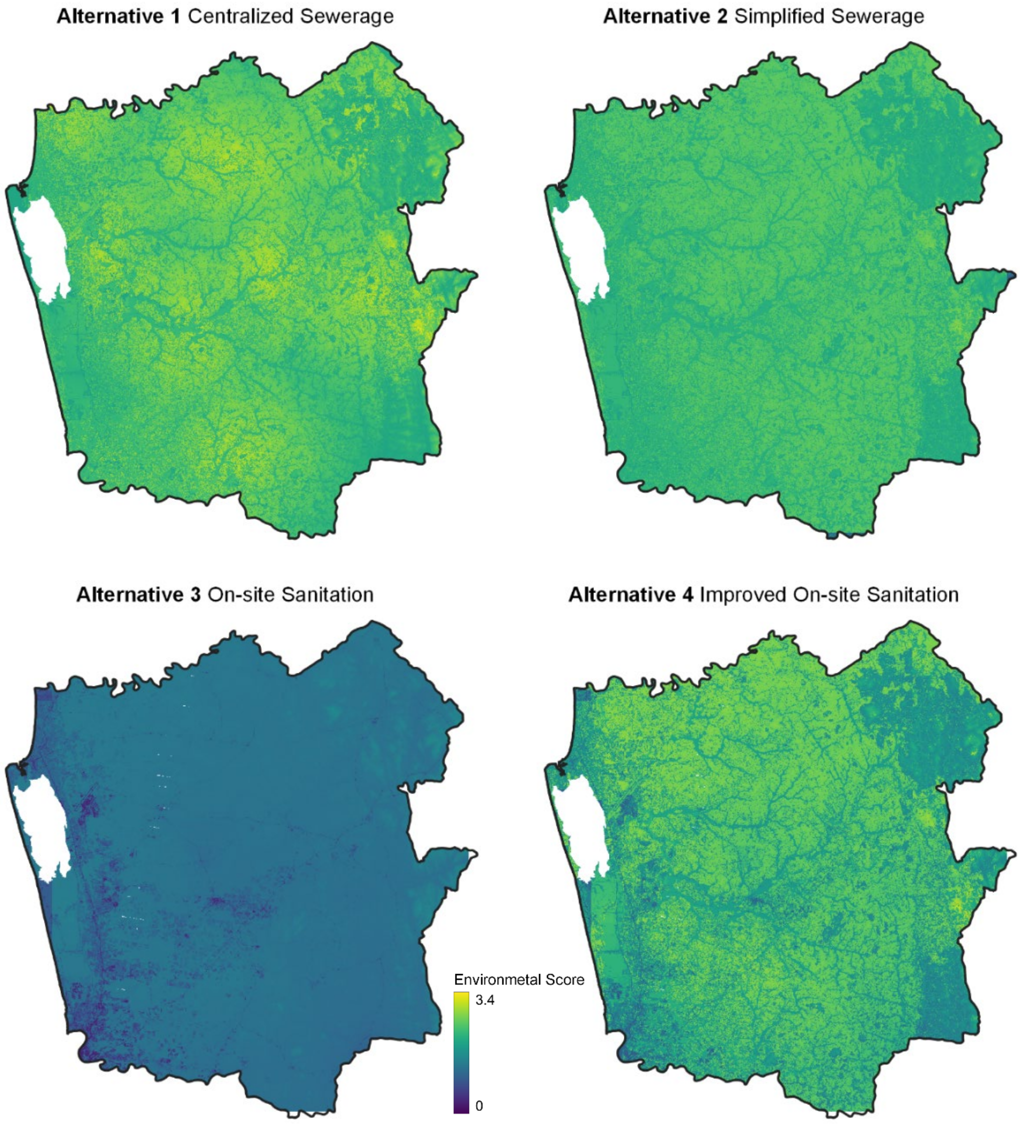


Figure 4.3 Results of environmental assessment

Owing to the setup of the four components of the environmental score, alternative 1 gives the highest values. Similar spatial patterns are visible in alternatives 1,2 and 4 with varying magnitudes. Alternative 3 has the lowest scores, especially in high-density and highly built-up areas. Land use based differences are more prominent in alternative 4 which is the one with most potential for water reuse, therefore sensitive to land use types.

4.4 Social assessment of the sanitation technology alternatives

Social assessment is conducted at the scale of the smallest administrative unit. Spatial analyses that are based on such abstract divisions are subject to errors attributed to Modifiable Areal Unit Problem (MAUP). Dasymetric mapping based on population distribution may be a suitable approach to avoid this problem (Mennis, 2003).

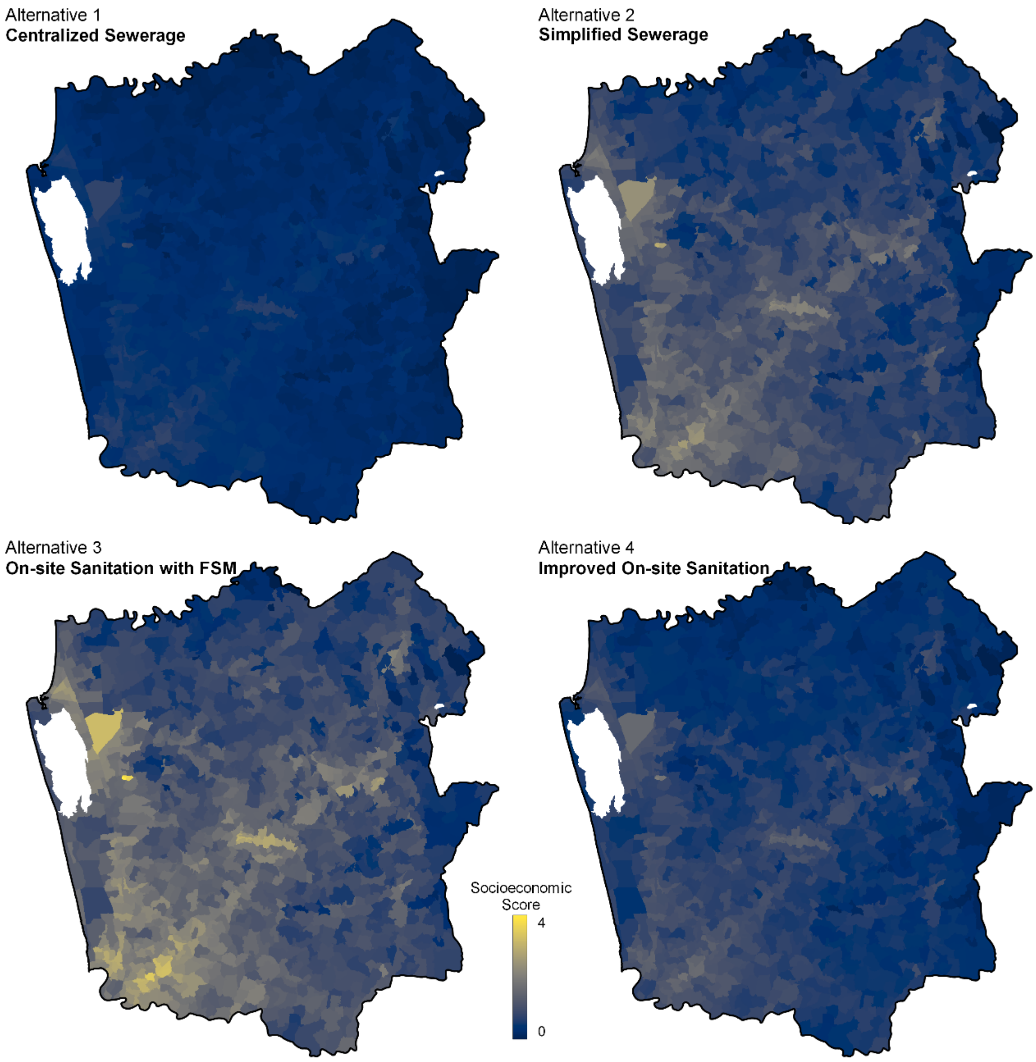


Figure 4.4 Results of social assessment

4.5 Sanitation Development Scenarios

Sanitation system distributions for the four scenarios are presented in the **figure 4.5**.

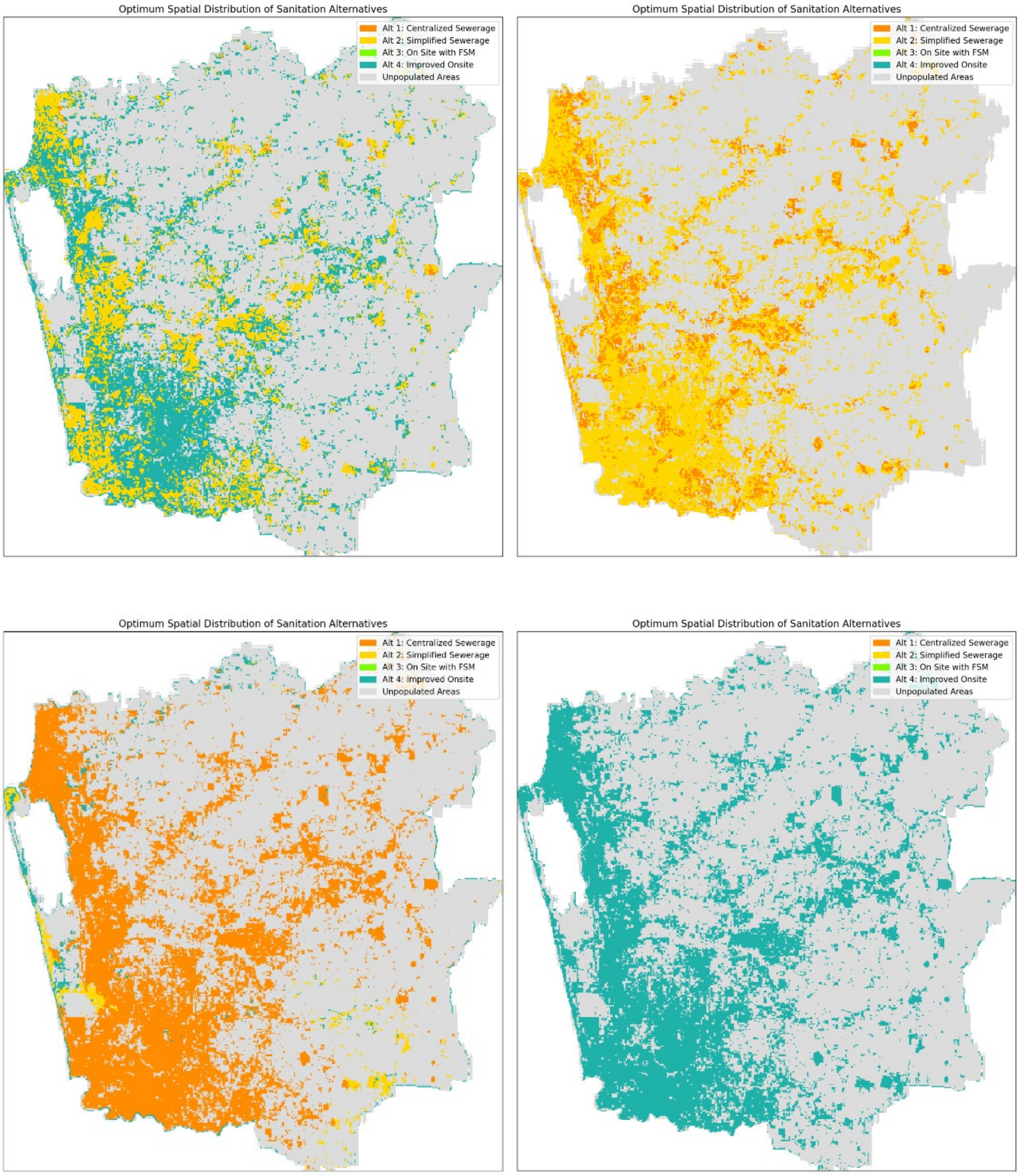


Figure 4.5 Optimum distribution of sanitation alternatives under four scenarios

While noting the results should be fine-tuned, some insightful observations can still be made. Under all four scenarios, the presence of simplified sewerage alternative is significant. Conventional centralized sewerage is confined to few clusters. Improved on-site sanitation is also significantly featured in three of the scenarios (1,2,3) and its spatial distribution is wider, along with a few easily identifiable clusters.

Overall, spatial distributions of the alternatives are highly fragmented. This property is unsuitable for an actionable sanitation plan. Therefore, post-processing may be necessary to produce distribution maps easily discernible regions with clear boundaries.

4.6 Development of actionable sanitation plans

4.6.1 Exploring sanitation scenarios

Sanitation planning process requires inputs from different stakeholders such as national and local governments, utility operators, communities, public health agencies and environmental organizations. Various professional backgrounds such as environmental engineers, hydrologists, economists, environmental scientists, public health officials and sociologists are represented in the planning process. These different parties have specific development objectives and therefore sometimes, competing priorities. The assessment framework used in this study that examines the sustainability in the aspects of economy, environment, and society, provides an opportunity to develop optimised sanitation plans under different levels of priorities given to the three pillars of sustainability and compare different possible development trajectories.

4.6.2 Post-processing results

The output maps produced by the described method has several features that are unsuitable for direct use as practicable sanitation plans and communication material for wider audiences. Sanitation plans in many scenarios are highly grainy, with different types of systems mixed together in many regions. Due to this, it is difficult to identify potential zones for different types of systems with any discernible boundary.

As a solution to this problem, the optimized sanitation plans were post-processed to reduce the noise. It was done by applying a median filter. Median filter is a popular algorithm in signal and image processing. It is a variant of the rank filter, which replaces the value in a grid cell with the specified ranking value in its specified neighbourhood. In the case of median filter, values are replaced by the median value of the neighbourhood. A larger neighbourhood produces a smoother image, but with a greater loss of information. A 12 x 12 pixels square neighbourhood is considered in this study.

4.7 Examination of selected scenarios

4.7.1 Scenario: Balanced development

The balanced scenario is defined by equal weightages to the aspects of economy, environment, and society. Optimised sanitation plan for this scenario is shown in **figure 4.6**.

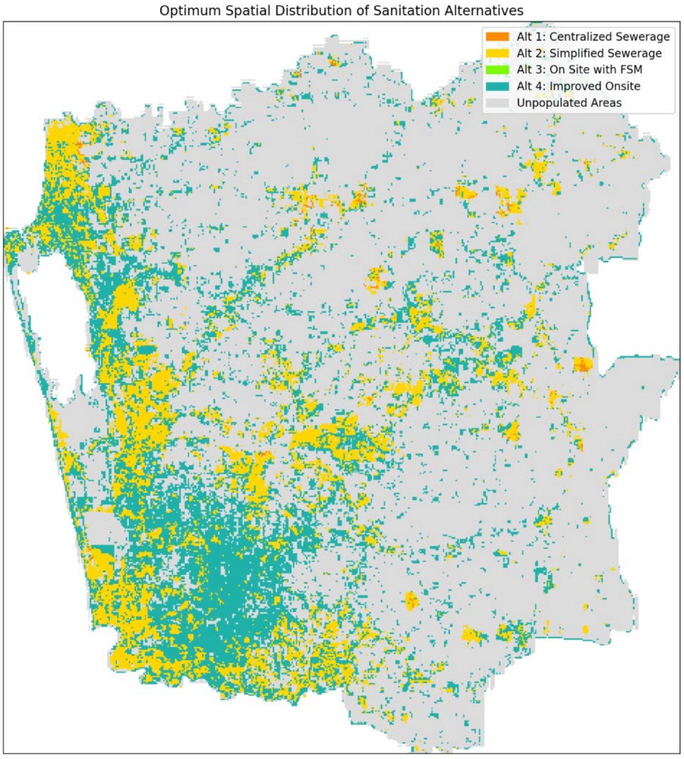


Figure 4.6 Optimus distribution of sanitation alternatives in the balanced scenario

This scenario primarily consists of only two of the four alternatives., namely the Alternative 2 Simplified Sewerage and Alternative 4 Improved Septic Tanks. As shown in the **figure 4.7**, alternative 4 leads in coverage area and population.

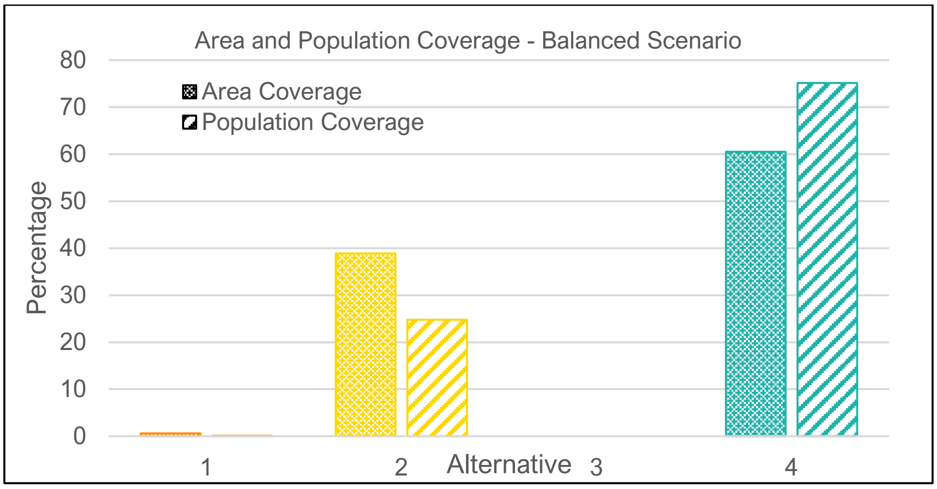


Figure 4.7 Area and population coverage of the alternatives in the Balanced Scenario

In the filtered map shown in **figure 4.8**, distinct regions can be clearly identified. Regions assigned with Alternative 2 are high density urban areas.

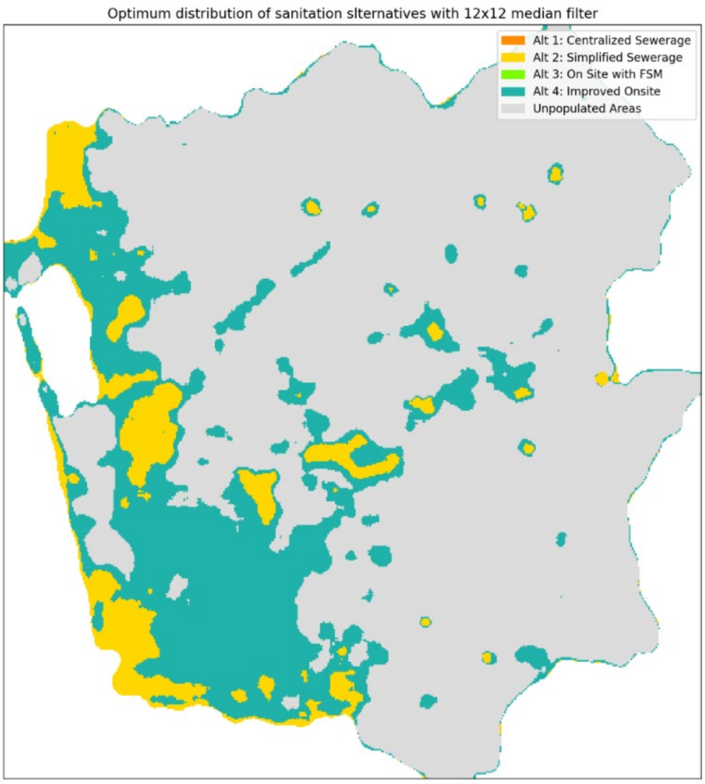


Figure 4.8 Optimised sanitation plan post-processed with a median filter

4.7.2 Scenario: Preference for economic and environmental benefits

A scenario that prioritises economic and environmental benefits over social aspects can be constructed by applying weightages of 10 for economic and environmental scores and a 0 for social score. Since the rate of adoption is the criteria used in the social score, this represents a scenario in which the adoption of the service by the public is not deemed important at the planning stage. For instance, if the government is supporting the service adoption as part of the project or through subsidies, then it will no longer be dependent on the socio-economic level of the households as assumed. In that case, sanitation planning can consider only the economic and environmental components of the evaluation. The optimised sanitation plan for such a scenario, as shown in **figure 4.9**, consists mainly of alternatives 1,2 and 4.

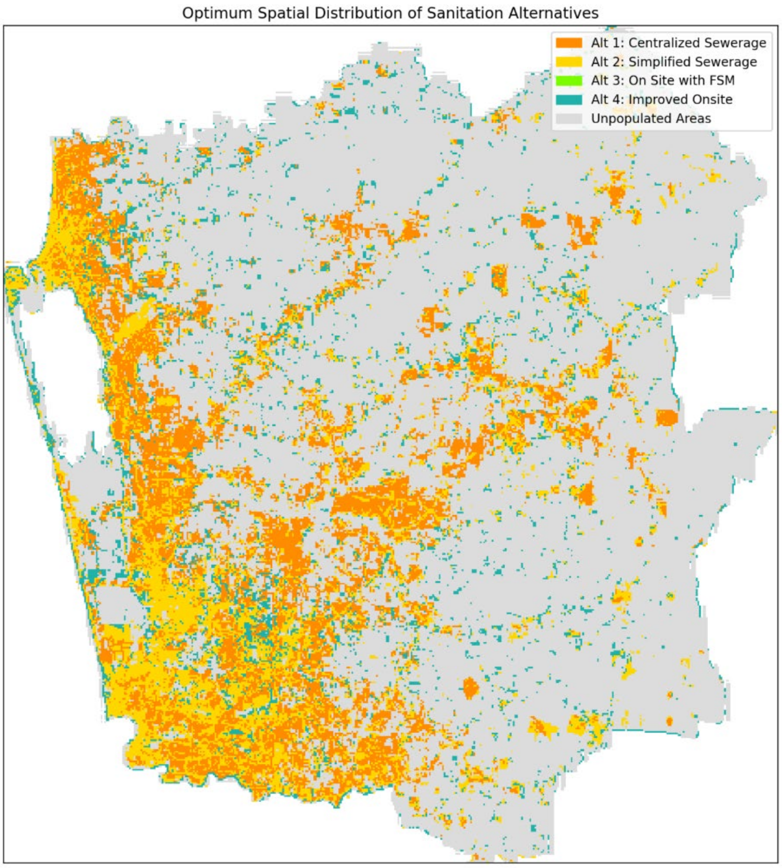


Figure 4.9 Optimum spatial distribution of the alternatives under the scenario for maximising economic and environmental benefits over social benefits

In this scenario, both centralised and simplified sewerage alternatives have been selected. In the original output, they are present across the whole area with no identifiable regions. By applying the median filter, the following map in figure X is prepared. There, the central high-density areas are designated alternative 1 centralised sewerage. Overlaying the previously selected WWTP locations, it can be seen that the alternative 1 regions have nearby WWTPs. Therefore, WWTPs to be considered for development under this scenario can be selected from the initial group for total coverage. Alternative 4 decentralised sanitation is clearly observed to be limited to the fringe areas outside the alternative 2 regions. This spatial pattern is suitable for implementation as the degree of centralisation is reduced gradually away from the population centres.

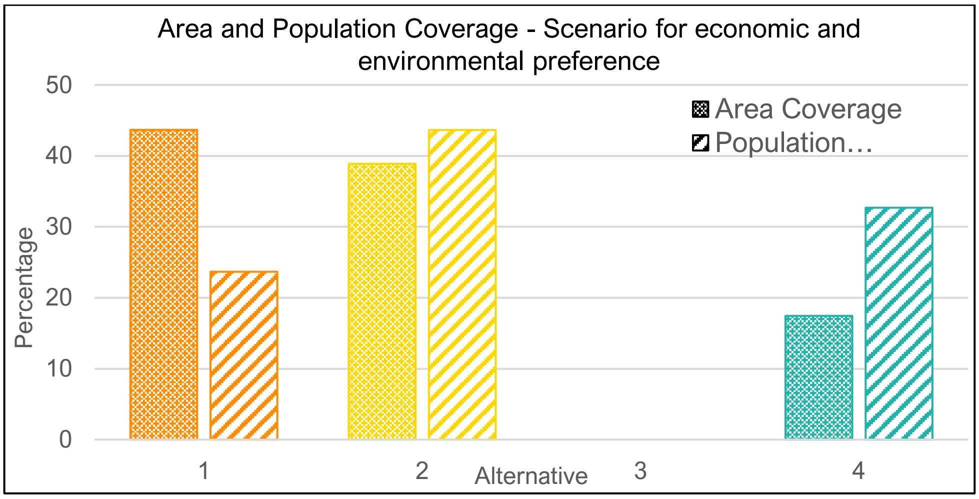


Figure 4.10 Area and population coverage of the alternatives in the scenario for maximising economic and environmental benefits over social benefits

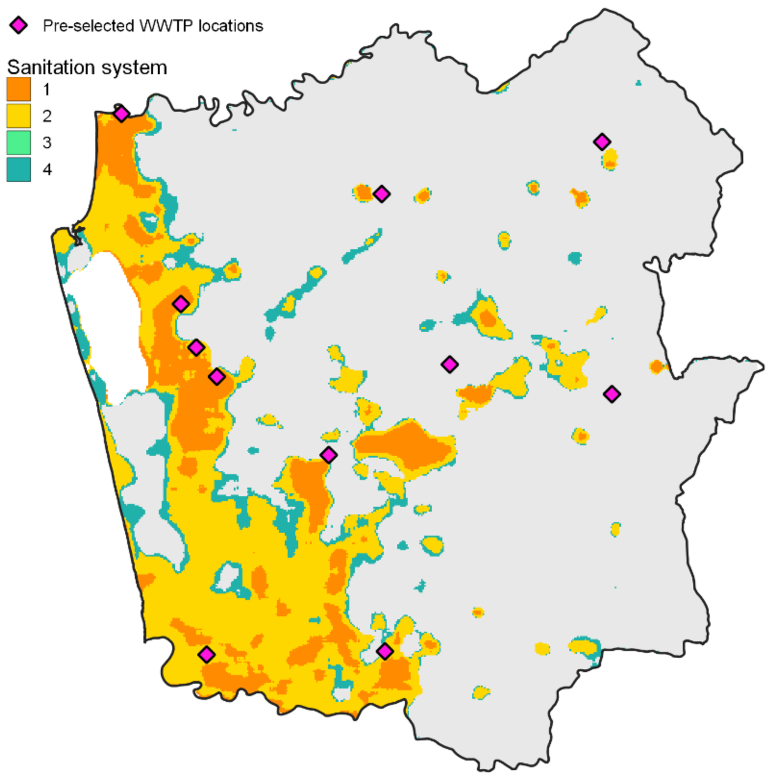


Figure 4.11 Optimised sanitation plan post-processed with a media filter

5 Conclusions and recommendations

Sanitation planning is evolving towards portfolio approaches, away from reliance on a single type of system. There is increasing awareness about the complex planning challenges of developing regions where settlement characteristics are heterogenous and highly dynamic. A spatially explicit sanitation planning framework becomes useful in this context. Objectives of this study were to commonly evaluate different sanitation systems on their suitability for a given location and develop optimized sanitation plans for different scenarios, identifying optimum spatial distribution of alternatives. It was also intended to develop tools and workflows to support the adoption of spatially explicit planning of portfolio solutions to sanitation planning practice.

These objectives were met through the evaluation framework, methodology and tools developed in this study. The use of the three pillars approach to sustainability i.e, economic, environmental, and social aspects, allowed a comprehensive evaluation of the sanitation technology alternatives. Through this approach, sanitation technologies best suited for a given place could be identified. Use of the familiar three pillars approach to sustainability will be conductive for adopting the developed framework into practice of sanitation planning. Development of the user-friendly scenario explorer will further support the adoption.

In many of the considered scenarios, optimised sanitation plan was a combination of technologies. This answers the initial research question on whether using a combined approach is more beneficial than a singular technology.

Consideration of the spatial variation of the suitability is a novel feature in this study, as available sanitation planning frameworks reviewed for this study do not offer the ability to consider spatial variation at high resolution. The method developed in study is unconstrained by political and administrative boundaries, which is often a limitation in spatial analysis and planning of sanitation systems.

5.1 General Recommendations

Guided by the finding that in most scenarios the optimum sanitation plan is a mix of multiple sanitation technology alternatives, it is recommended to adopt a portfolio approach towards sanitation planning. Inclusion of technologies with varying levels of centralisation and technological sophistication will allow to generate solutions that are well-suited for the local conditions.

However, consideration of portfolio approaches in practical settings mean changing the present philosophy and processes in sanitation planning. To encourage such a drastic change, it is necessary to provide strong evidence of its comparative advantages thorough academic studies. Therefore, further studies in topics such as enhancing the evaluation frameworks and case studies in different settings are recommended.

5.2 Specific recommendations for Gampaha District

Simplified sewerage is prominently featured in many scenarios. Especially in many balanced scenarios, simplified sewerage is allocated a higher area and population than centralised sewerage. However, simplified sewerage is not considered in the sanitation master plans for this area. Simplified sewerage has only been applied in Sri Lanka at a limited scale, often in sanitation projects for the urban poor. In line with the outcomes of this study, it is recommended that simplified sewerage be considered as an option municipal sanitation service, in Gampaha district and similar contexts.

Improved septic tanks are also prominent in many optimised sanitation plans. It is observed that it has been prioritised for low-density areas that are close to water bodies, such as coastal areas and low-lying areas. This technology is at its inception in Sri Lanka and is yet to see wide-scale adoption. But similar technologies have been used successfully around the world in similar environments. Therefore, refining this technology and promotion of its adoption is recommended.

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