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

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Abstract

When planning sanitation systems for developing regions with heterogenous settlement characteristics, it is desirable to consider a portfolio of solutions allowing to select the most appropriate for a given location. In this study, we develop a framework for spatially explicit evaluation of sanitation system alternatives in terms of their economic, environmental, and social benefits. At the present stage of this study, we develop data-driven and spatial analysis-based methods to evaluate sanitation system alternatives. We consider annual cost as the metric for economic assessment and expected rate of adoption for social assessment. For environmental assessment, we combine four metrics, namely 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. By exploring different development scenarios defined by the levels of preference for economic, environmental and social appropriateness, it is found that optimum sanitation plans under many scenarios are a combination of centralised and decentralised systems.

Keywords Sewerage, Decentralized Sanitation, Sanitation Planning, Spatial Optimization

1. Introduction

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). 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. 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. Previous researchers like Tilley (2014) and Spuhler and Roller (2020) have compiled information on a broad range of sanitation technology alternatives.

There are specific strengths to different technologies and approaches. It is understood that centralized approaches are generally 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 investigates the above premise and has the objective of finding what combination of sanitation systems out of a portfolio consisting of both centralized and decentralized technologies, provides the best outcomes. For this purpose, it was intended to develop a common framework for evaluation of the sustainability of the sanitation system alternatives. Optimum spatial distribution of the sanitation alternatives under different development scenarios was intended to be the primary output of this study. These findings are expected to provide a basis for planning and policy recommendations that can transform the conventional approach to sanitation.

1.1 Background

1.2 Sustainable Sanitation

Many researchers and practitioners have focussed on evaluating the sustainability of sanitation systems and have developed several sustainability frameworks for this purpose. 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, Schweitzer and Lockwood, (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.

1.3 Sanitation Planning: Present status and necessary improvements

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, Tarhini and Nasr, 2009). 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).

However, decentralized sanitation systems are increasingly more attention on decentralized sanitation, not as a secondary option after conventional sewerage but a priority. Also, there is an understanding that top-down approaches to planning are less effective for solving sanitation challenges in developing world (Kalbermatten, 1982). It is recognized that a sanitation technology selected for a certain area needs to be socially and culturally acceptable, environmentally beneficial, sufficiently satisfies public health needs, technologically appropriate, affordable and manageable (Spuhler *et al.*, 2020).

Considering such requirements, many sanitation planning frameworks have been developed and applied. Sanitation planning frameworks generally attempt to address the needs of a specific area and support decision making regarding investments on sanitation improvements (Törnqvist *et al.*, 2008). Many available sanitation planning frameworks usually focus on a specific type of location or population group 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 (Kar and Chambers, 2008). Similarly, there are other frameworks focusing on urban (Parkinson and Lüthi, 2014) and Peri-urban(Törnqvist *et al.*, 2008) settings.

However, 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.

1.4 Status of sanitation in Sri Lanka and Gampaha District

Sri Lanka has achieved a high coverage of basic sanitation but the access to safe and improved sanitation is limited. Coverage of centralized sewer systems is only about 2 %. About 92 % of the population rely on on-site facilities. Surveys have revealed that about 80% of the on-site facilities are not properly constructed septic tanks with soakage pits (JICA, 2017). Most are simply collection pits, and the drainage conditions are often poor in most places in the wet zone, which encompasses many of

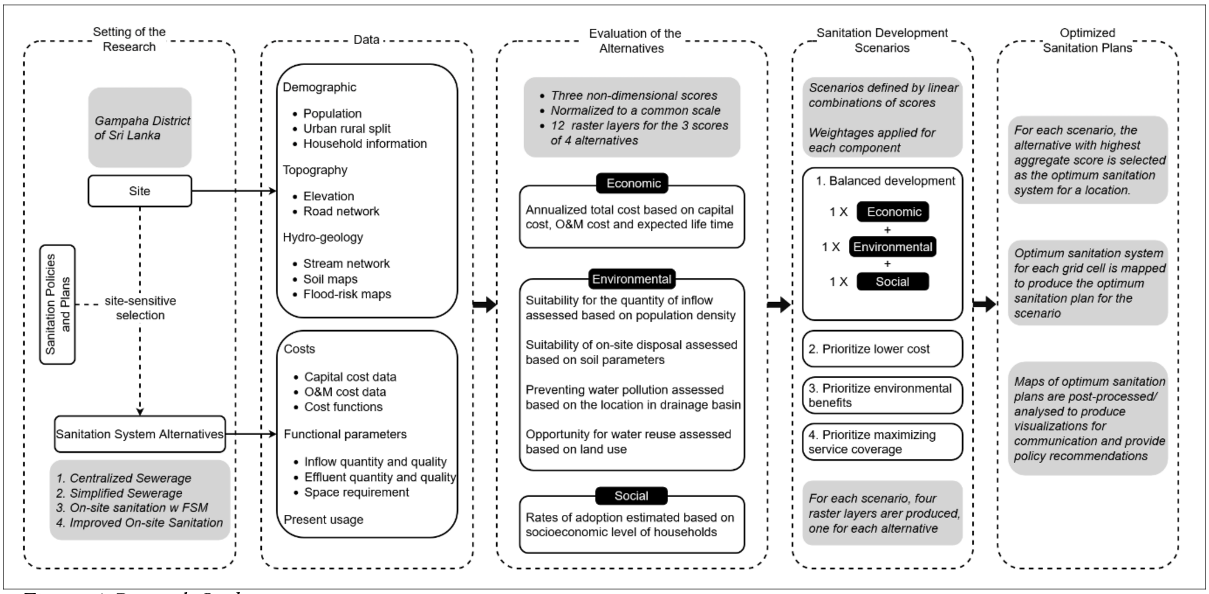

Figure 1 *Research Outline*

the most populous urban regions. While Sri Lanka has standardized the on-site systems in the SLS745 specifications (Sri Lanka Standards Institution, 2009) there is no enforcement for residential systems.

The selected study area, Gampaha District, with an area of 1,387 km^2, is located in western Sri Lanka. It has a tropical monsoon climate. Annual rainfall is 2,024 mm (2013), and the average temperature is 28°C. The population is about 2.29 million, and the mean household income is 38,807 LKR. There are only two municipal sewerage projects in the district, and they only serve about 16,000 persons altogether.

2. Research outline and present activities

2.1 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.

1. Conventional centralized sewerage
2. Simplified sewerage
3. On-site sanitation with Faecal Sludge Management (FSM)
4. Improved on-site sanitation

Individual units in the sanitation service chain from toilet facilities to final disposal are described in detail in **Table 1**.

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 1** summarizes the research outline.

2.2 Summary of previous work

Early stages of this research focussed on exploring suitable evaluation criteria considering the ability to evaluate all considered alternatives. Data availability was another consideration because of mismatch of time-periods of data, spatial coverage, and resolution. After an extensive survey of data sources and relevant literature on evaluation of sanitation systems, above mentioned six criteria were finalized.

Evaluation of the economic score, explained by the annual total cost, was attempted first. Spatial distribution of the cost of centralized sewerage was understood to be sensitive many topographical, physical, hydro-geological, and socio-economic

Table 1 *Sanitation System Alternatives*

	1 Centralized	2 Semi	3 Decentralized	4 Decentralized - Improved
Toilet	Cistern Flush toilet Pour Flush toilet	Cistern Flush toilet Pour Flush toilet	Cistern Flush toilet Pour Flush toilet	Cistern Flush toilet Pour Flush toilet
On-site storage/ treatment		Interceptor tanks	Septic tanks	Improved septic tanks with anaerobic filtration and disinfection
Collection	Conventional Gravity Sewers	Emptying and transport of intercepted solids with vacuum trucks Solids-free sewer Simplified sewer	Emptying and transport with vacuum trucks	Emptying and transport with vacuum trucks
Centralized Treatment	Biological wastewater treatment. Pre-treatment to disinfection. Sludge treatment and drying Sludge co-composting	Small to medium wastewater treatment plants, DEWATS systems Sludge treatment and drying Sludge co-composting	Faecal Sludge Treatment Sludge treatment and drying Sludge co-composting	Faecal Sludge Treatment Sludge treatment and drying
Disposal	Treated effluent Discharge to water bodies Sludge disposal to landfills	Treated effluent Discharge to water bodies Sludge disposal to landfills	Treated effluent Discharge to water bodies Sludge disposal to landfills	Treated effluent Discharge to water bodies Sludge disposal to landfills
Reuse/ Recycle	Irrigation Water Recharge Application of composed sludge	Irrigation Water Recharge Application of composed sludge	Irrigation Water Recharge Application of composed sludge	Local water reuse - Home gardens
Reason for selection	Benchmark alternative representing the conventional approach to sanitation	An intermediate approach with a few existing applications in Sri Lanka.	A low-cost decentralized approach to sanitation that can be directly scaled up from the present conditions	A costlier decentralized alternative with better pollution reduction and opportunity for local water reuse

parameters of the area. The spatially distributed cost of centralized sewerage in alternative 1 was estimated using a data-driven cost prediction model which was discussed in detail in the previous reports.

This paper describes evaluation of economic score of remaining alternatives, (2,3 and 4) and environmental and social score of all four alternatives. Methodology of developing optimized sanitation plans under different scenarios is also discussed, presenting preliminary results.

3. Data and Methods

3.1 Selection of Sanitation system alternatives

Four sanitation system alternatives were selected for analysis, considering suitable and likely options that are considered in Sri Lanka's sanitation planning. Especially, reference was made to the *Sanitation Master Plan 2021-2030* (NWSDB, 2021). Descriptions of the selected alternatives are presented in **Table 1**. Centralized sewerage was selected as the Alternative 1 to represent the conventional approach to sanitation. Simplified Sewerage systems are also sewer based but system components are smaller and design tolerances are relaxed. This is justified by using intervention chambers at user premises to 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. Alternative 3 includes on-sites septic tank systems and centralized Faecal Sludge Management (FSM). This represents a direct succession of the present status of sanitation in the study area. In alternative 4, an improved version of the standard septic tanks introduced by the National Water Supply & Drainage Board (NWSDB) is considered. It is equipped with anaerobic filters and disinfection units to achieve a much better effluent quality. Therefore, local water reuse become a viable option in this alternative.

3.2 Economic assessment of alternatives

Total annual cost is selected as the metric for economic assessment of the sanitation alternatives.

Total annual cost is estimated as the sum of the annualized capital cost and the annual operation and maintenance cost. For the purpose of this study, it was necessary to not only estimate the total cost for the study area but also the spatial distribution of cost within the area. Spatial distribution of the cost of centralized sewerage in alternative 1 was estimated using a data-driven cost prediction model which was presented previously.

For other alternatives, it was assumed that the spatial distribution of cost was primary associated with population density and therefore estimated based on per capita cost and population distribution. Per capital costs were selected referring relevant data sources for Sri Lanka or similar settings(OECD, 2005; NWSDB, 2021). **Supporting Information S1** presents the methodology for estimation of costs of the alternatives 2,3 and 4.

3.3 Environmental assessment of alternatives

Limits of Population Density for Sanitation System Selection

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 S2** in Supporting Information is an excerpt from the relevant national standard of Sri Lanka, SLS 745 (Sri Lanka Standards Institution, 2009).

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). 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. Methodology of estimation is presented in **Supporting Information S3**.

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 2** is a map of the study area showing the index value.

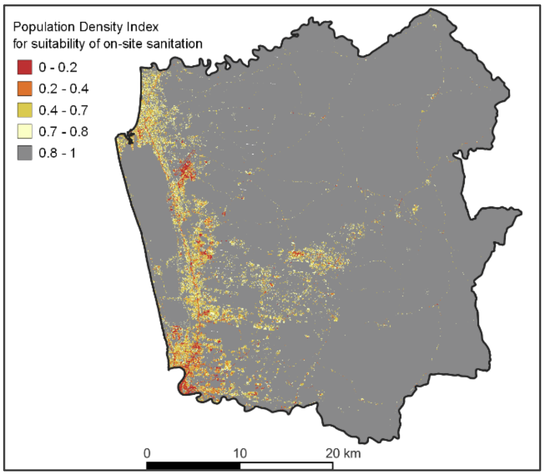

Figure 2 *Population density index for suitability of on-site sanitation*

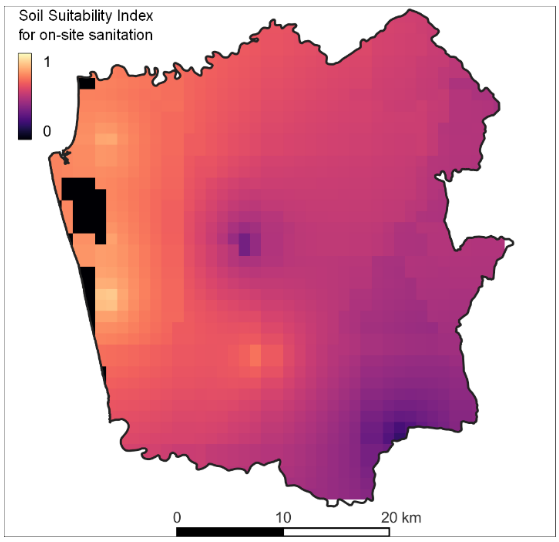

Figure 3 *Soil Suitability Index*

Suitability of Soil for On-site Disposal

Properties of the soil has an impact on on-site effluent disposal because 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. However, in many states in the USA, suitability of soils is assessed based on Long-Term Acceptance Rate which is a more comprehensive measure that accounts for composition, texture, colour, and structure of soil in 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).

A soil suitability index value is calculated based on the percentages of the three soil texture components. **Table 2** 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.

Table 2 *Components of soil suitability index*

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

Height Above the Nearest Drainage (HAND)

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 used in this study as a proxy for flood risk.

HAND model was derived using the Vaessa DEM (World Bank Group, 2020) which gives elevations at 20 m resolution. Starting from the DEM, the area was delineated to sub catchments and stream network was traced. Within each sub catchment, height difference between the outlet and each grid cell was calculated. Final HAND model is then rescaled to between 0 and 1. **Figure 4** shows the HAND model for the area.

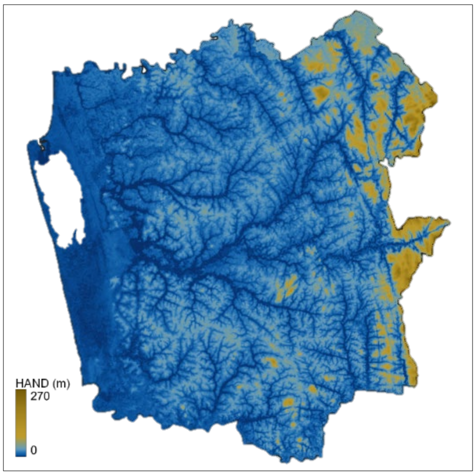

Figure 4 *Left: Height Above Drainage (HAND) model*

Water reuse potential based on land use

Potential for water reuse has been mapped based on the land use. 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 4** presents the evaluation scheme. Ratings were given based on researcher's judgement. Map of water reuse potential generated by applying the evaluation scheme is presented in **Figure 5**.

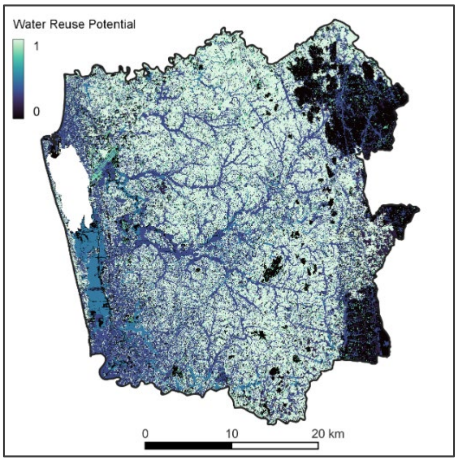

Figure 5 *Water reuse potential based on land use*

Table 3 *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	0	0	No demand	0
Mangroves	0	0	No demand	0
Marsh	1	2	Limited demand for water recharge. Adoption is difficult	0.5
Wetland	1	2	Limited demand for water recharge. Adoption is difficult	0.5
Coconut/ Palm tree dominated	3	3	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	1	1	Demand is low as paddy fields in wet zone are continuously irrigated with canal system with no shortage of water.	0.33
Rubber	1	0	Rubber crops are generally not irrigated. Plantations have no infrastructure to receive reclaimed water.	0.167
Dense Forest	0	0	No demand	0
Forest Plantation	1	1	Limited demand	0.33
Open Forest	0	0	No demand	0
Grassland	2	3	Demand for watering grass fields. Easier adaptation as closer to points of generation.	0.833
Scrubland	0	0	No demand	0
Built up area	1	1	Limited demand for purposes like urban farming and washing. Adoption requires new infrastructure.	0.33

Above described four indices are modified with appropriate multipliers for the selected sanitation system alternatives, as presented in **Table 4**. 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 4** summarizes the modifiers for all alternatives.

Table 4 *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

3.4 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. Based on authors judgement, supported by available literature (Moseti, Kimani and Mutua, 2009; Mulatya *et al.*, 2021) on choice of sanitation system and willingness to pay, the four alternatives were ranked in the order of least to highest expected rate of adoption as follows.

1. Alternative 1: Centralized Sewerage
2. Alternative 4: Improved Septic Tanks
3. Alternative 2: Simplified Sewerage
4. Alternative 3: On-site Sanitation and Faecal Sludge Treatment

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 in a suitable level of detail. While there are several poverty maps developed for Sri Lanka (Amarasinghe, Samad and Anputhas, 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 higher resolution analysis.

An exercise of mapping the socioeconomic level was 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, 2015). 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 6** shows the socioeconomic index for Gampaha district. Higher values indicate a higher socio-economic level.

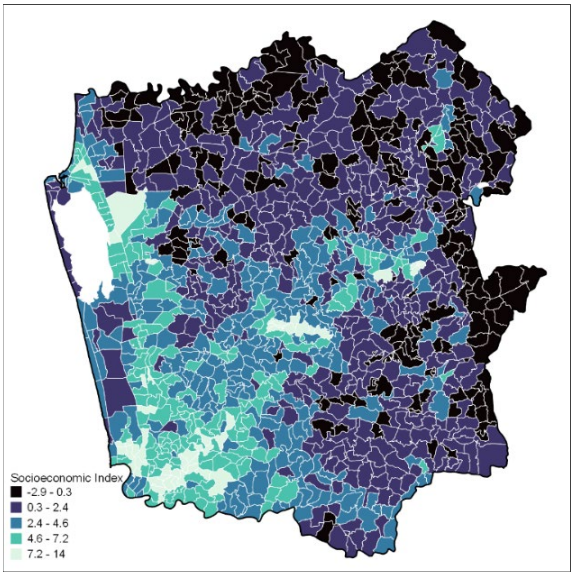

Figure 6 *Socioeconomic Index for Gampaha District, calculated at the scale of admin division level 4.*

3.5 Sanitation scenarios

Sanitation 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. Therefore, logarithms of cost values are calculated first, which are then linearly rescaled. Environmental and social indices are directly rescaled.

For each scenario, linear combinations of individual raster layers with above weightages applied were 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.

4. Results and Discussion

4.1 Evaluation of individual alternatives

Economic assessment

Cost distribution of alternatives 2,3 and 4 follow the spatial pattern of population because these estimated based on per capita cost. Centralized sanitation in alternative 1 has a distinct pattern. Here the costs are aggregated mainly around the road network. Here too the influence of population is visible. **Figure 7** shows the results of economic assessment

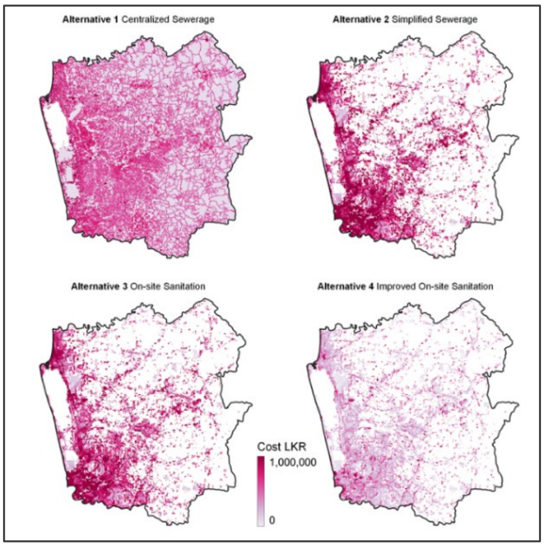

Figure 7 *Results of economic assessment as the cost of each alternative in LKR*

Environmental Assessment

Environmental scoring of the four alternatives prepared by combining the modified evaluation raster layers are presented in **figure 8**.

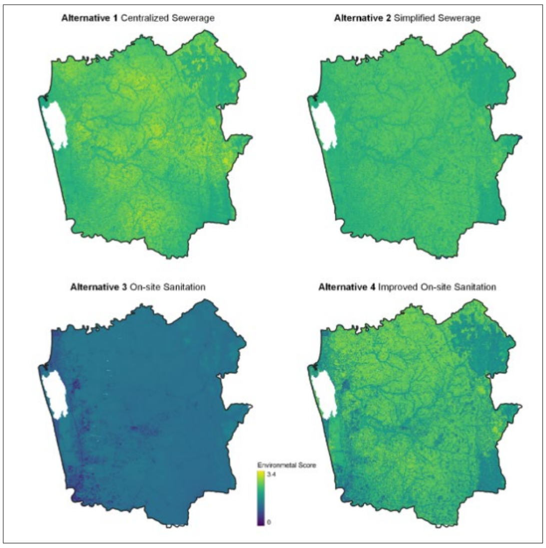

Figure 8 *Results of environmental assessment*

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.

Social assessment

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).

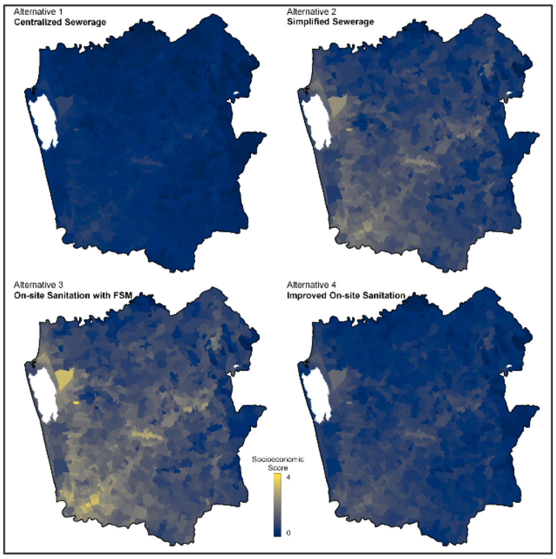

Figure 9 *Results of social assessment*

4.2 Sanitation Development Scenarios

Optimum sanitation plan for a selected scenario, defined by weightages for economic, environmental, and social scores specified as 10,10 and 0 respectively, is shown in figure 10.

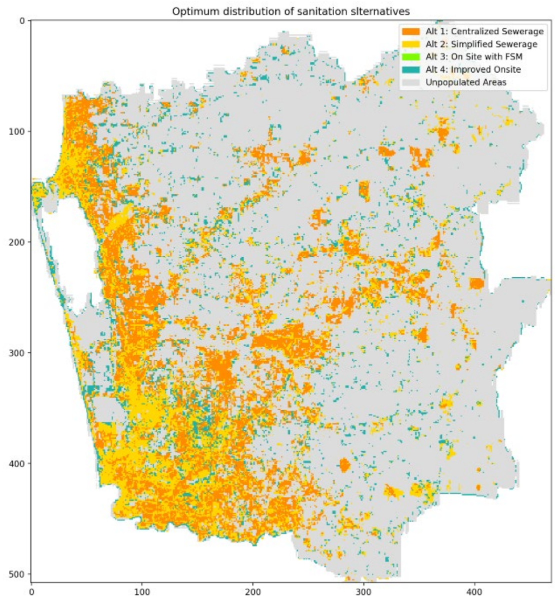

Figure 10 Optimum sanitation plan for a selected scenario

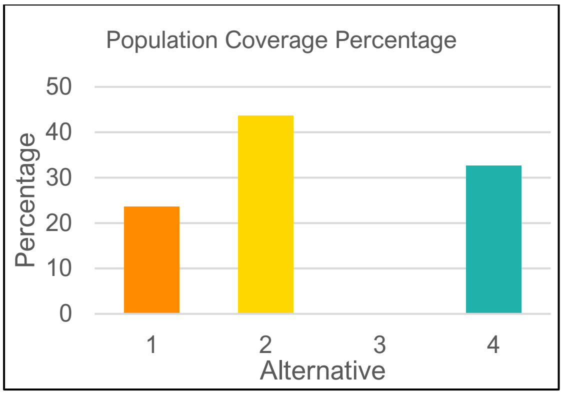

Figure 11 Population coverage in the optimum sanitation plan for the selected scenario

As shown in figure 11, alternative 2 Simplified Sewerage serves most people in this plan. Centralised sewerage has been specified for some of the higher density areas. Improved septic tanks have been specified for low-density and low lying areas.

5. Conclusion and Remarks

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.

In many scenarios, the optimum sanitation plan was found to be a mixture of different sanitation systems. The online interactive scenario explorer developed in this study can be useful for easily developing and comparing different sanitation plans to suit different development priorities.

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.

Based on the results on this study, it is recommended to consider portfolio approaches to sanitation planning, specially for places with heterogeneous settlement characteristics. Specifically, for Gampaha district of Sri Lanka, it is recommended to consider simplified sewerage systems in future masterplans as it is heavily featured in many scenarios. Further development of improved septic tanks technology is also recommended.

Acknowledgement
National Water Supply Drainage Board of Sri Lanka provided data regarding their sewerage systems and plans that were instrumental in conducting this study

6. Reference

1. Amarasinghe, U., Samad, M. and Anputhas, M. (2005) ‘Spatial clustering of rural poverty and food insecurity in Sri Lanka’, *Food Policy*, 30(5–6), pp. 493–509. doi:10.1016/j.foodpol.2005.09.006.
2. Barnes, R. and Ashbolt, N. (2006) ‘Review of decision tools and trends for water and sanitation development projects’.
3. Boulenouar, J., Schweitzer, R. and Lockwood, H. (2013) *Mapping sustainability assessment tools to support sustainable water and sanitation service delivery*. Working Paper Working Paper 6. IRC International Water and Sanitation Centre, p. 26.
4. Brown de Colstoun, E.C. *et al.* (2017) ‘Global Man-made Impervious Surface (GMIS) Dataset From Landsat’. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). Available at: https://doi.org/10.7927/H4P55KKF.
5. Chandrasiri, G. and Samarakoon, L. (2008) ‘Spatial patterns and geographic determinants of poverty in Sri Lanka: Linking poverty mapping with geoinformatics’, in *Asian Conference on Remote Sensing (ACRS) Colombo, Sri Lanka*.
6. Department of Census & Statistics (2015) *Census of Population and Housing*. Ministry of Policy Planning and Economic Affairs.
7. Dias, V. *et al.* (2020) ‘Mapping Poverty and Wealth: An Alternative Socioeconomic Index for Sri Lanka’. LIRNEasia. Available at: https://lirneasia.net/2020/01/mapping-poverty-and-wealth-an-alternative-socioeconomic-index-for-sri-lanka/.
8. DWA (2013) ‘FIETS Sustainability Approach’. Dutch WASH Alliance. Available at: https://web.archive.org/web/20140412062343/https://www.washalliance.nl/wp-content/blogs.dir/2/files/sites/2/2013/04/fiets_sustainability_approach.pdf.

9. Elkington, J. (2018) '25 Years Ago I Coined the Phrase "Triple Bottom Line." Here's Why It's Time to Rethink It.', *Harvard Business Review*, 25 June. Available at: https://hbr.org/2018/06/25-years-ago-i-coined-the-phrase-triple-bottom-line-heres-why-im-giving-up-on-it (Accessed: 26 January 2022).

10. Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University (2016) 'High Resolution Settlement Layer (HRSL)'. Source imagery for HRSL © 2016 DigitalGlobe. Available at: https://www.ciesin.columbia.edu/data/hrsl.

11. Hutton, G. and Varughese, M. (2016) *The Costs of Meeting the 2030 Sustainable Development Goal Targets on Drinking Water, Sanitation, and Hygiene*. World Bank, Washington, DC. doi:10.1596/K8543.

12. IRC (2016) *Building blocks*, *Water Services That Last*. Available at: https://web.archive.org/web/20160317034001/http://www.waterservicesthatlast.org/resources/building_blocks (Accessed: 25 January 2022).

13. JICA (2017) *Final Report: The project for the strategic master plan under the sewerage sector in the Democratic Socialist Republic of Sri Lanka (phase 1)*. Japan International Cooperation Agency.

14. Kalbermatten, J.M. (ed.) (1982) *Appropriate sanitation alternatives: a planning and design manual*. Baltimore: Published for the World Bank [by] the Johns Hopkins University Press (World Bank studies in water supply and sanitation, 2).

15. Kar, K. and Chambers, R. (2008) *Handbook on community-led total sanitation*. Institute of Development Studies.

16. Kerstens, S.M. *et al.* (2016) 'A new approach to nationwide sanitation planning for developing countries: Case study of Indonesia', *Science of The Total Environment*, 550, pp. 676–689. doi:10.1016/j.scitotenv.2016.01.104.

17. Massoud, M.A., Tarhini, A. and Nasr, J.A. (2009) 'Decentralized approaches to wastewater treatment and management: Applicability in developing countries', *Journal of Environmental Management*, 90(1), pp. 652–659. doi:10.1016/j.jenvman.2008.07.001.

18. Mennis, J. (2003) 'Generating Surface Models of Population Using Dasymetric Mapping', *The Professional Geographer*, 55(1), pp. 31–42. doi:10.1111/0033-0124.10042.

19. Moseti, Y.K., Kimani, S. and Mutua, B. (2009) 'The linkage between settlement profile and choice of sanitation system in peri-urban areas: A case study of Nakuru municipality', *undefined* [Preprint]. Available at: https://www.semanticscholar.org/paper/The-linkage-between-settlement-profile-and-choice-A-Moseti-Kimani/cf96000c51efcac9262dc8870fcc2be3f88f1216 (Accessed: 23 January 2022).

20. Mulatya, D.M. *et al.* (2021) 'Willingness to pay for improvements in rural sanitation: Evidence from a cross-sectional survey of three rural counties in Kenya', *PLOS ONE*. Edited by R. Calabrese, 16(5), p. e0248223. doi:10.1371/journal.pone.0248223.

21. Nobre, A.D. *et al.* (2011) 'Height Above the Nearest Drainage – a hydrologically relevant new terrain model', *Journal of Hydrology*, 404(1–2), pp. 13–29. doi:10.1016/j.jhydrol.2011.03.051.

22. NWSDB (2021) 'Sanitation Masterplan 2021-2030'. National Water Supply & Drainage Board.

23. OECD (2005) *Rural cost functions for water supply and sanitation*. P-60777-A-1. OECD EAP Task Force Secretariat. Available at: https://www.oecd.org/env/outreach/36228167.pdf.

24. Okurut, K. *et al.* (2015) 'Assessing demand for improved sustainable sanitation in low-income informal settlements of urban areas: a critical review', *International Journal of Environmental Health Research*, 25(1), pp. 81–95. doi:10.1080/09603123.2014.893570.

25. Parkinson, J. and Lüthi, C. (2014) *Sanitation 21: A Planning Framework for Improving: City-Wide Sanitation Services*. IWA.

26. Robbins, D.M. and Ligon, G.C. (2014) *How to Design Wastewater Systems for Local Conditions in Developing Countries*. IWA Publishing. doi:10.2166/9781780404776.

27. Roux, P. *et al.* (2011) 'Urban planning of sewer infrastructure: Impact of population density and land topography on environmental performances of wastewater treatment systems', in.

28. Spuhler, D. *et al.* (2020) 'Developing sanitation planning options: A tool for systematic consideration of novel technologies and systems', *Journal of Environmental Management*, 271, p. 111004. doi:10.1016/j.jenvman.2020.111004.

29. Spuhler, D. and Roller, L. (2020) 'Sanitation technology library: details and data sources for appropriateness profiles and transfer coefficients'. Eawag: Swiss Federal Institute of Aquatic Science and Technology. doi:10.25678/0000SS.

30. Sri Lanka Standards Institution (2009) *Code of Practice for the Design and Construction of Septic Tanks and Associated Effluent Disposal Systems Part 2: Systems Disposing to Surface, Systems for On-Site Effluent Reuse and Larger Systems Disposing to Ground (First Revision)*. SLS 745 Part 2: 2009. Colombo: Sri Lanka Standards Institution.

31. Tilley, E. *et al.* (2014) *Compendium of Sanitation Systems and Technologies*. 2nd revised edition. Zurich:

Eawag: Swiss Federal Institute of Aquatic Science and Technology. Available at: https://www.eawag.ch/en/department/sandec/publications/compendium/.

32. Törnqvist, R. *et al.* (2008) 'A framework for planning of sustainable water and sanitation systems in peri-urban areas', *Water Science and Technology*, 58(3), pp. 563–570. doi:10.2166/wst.2008.702.

33. UNEP/GPA Coordination Office (2004) *UNEP/WHO/HABITAT/WSSCC: Guidelines on Municipal Wastewater Management*. The Hague, The Netherlands.

34. University of Illinois Extension (no date) *Septic Systems in Illinois*, *Septic Systems in Illinois*. Available at: https://web.extension.illinois.edu/septicsystems/ (Accessed: 30 November 2021).

35. Vyas, S. and Kumaranayake, L. (2006) 'Constructing socio-economic status indices: how to use principal components analysis', *Health Policy and Planning*, 21(6), pp. 459–468. doi:10.1093/heapol/czl029.

36. World Bank (2005) *A Poverty Map for Sri Lanka—Findings and Lessons*. Washington D.C.: The World Bank. Available at: https://www.ciesin.columbia.edu/repository/povmap/methods/Sri_Lanka_povmap.pdf.

37. World Bank Group (2020) 'Sri Lanka - Digital Elevation Model'. World Bank Group and European Space Agency. Available at: https://wbwaterdata.org/dataset/sri-lanka-digital-elevation-model.

Supporting Information

S1 Estimation of Annualized cost of Alternatives 2,3, and 4

For Alternative 2 simplified sewerage, rates for year 2005 were referred from *Rural cost functions for water supply and sanitation* (OECD, 2005). The values euro were inflation-adjusted to 2020, based on historical values of the euro. Inflation Calculator tool available at https://www.inflationtool.com/euro was used for this purpose.

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

Considering an exchange rate of 220:1 2020 EUR rates were then converted to Sri Lankan Rupee (LKR).

For alternatives 3 and 4, rates estimated in NWSDB's *Sanitation Masterplan 2020-2030* 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. Per capita cost estimation is summarized in the table below.

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

Spatial distribution of cost was prepared by multiplying the population layer by the per capita costs.

S2 Minimum 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 (m3/day)	Minimum distance between soakage pits (m)
< 2	10
2 -5	15
5 – 10	20
10 -30	36

S3 Calculation of population density threshold

The two extreme cases shown below 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 S2**. In the densest arrangement with 10 m distance between soakage pits, allowable flow rate is 2 m^3/day for each, totalling to 18 m^3/day within 30 m grid cell. Between these two extremes, a flow rate of 20 m^3/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)*.