Assessment of high-value near-term engineering innovations for Indian sanitation

by

Elliott S. Donlon

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Author . . . .
Department of Mechanical Engineering
August 31, 2020

Certified by . . . .
Amos G. Winter, V
Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by . . . .
Nicolas G. Hadjiconstantinou
Professor of Mechanical Engineering
Graduate Officer

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Abstract

This study presents the Sanitation Needs and Innovation (SaNI) framework for identifying underserved populations and gaps between their sustainable sanitation requirements and sanitation system performance. Safe, sustainable sanitation is a vital, frequently unmet need – especially in low and middle-income countries. In India alone, economic losses from poor sanitation are estimated to be \$53.8 billion annually, or 6.4% of the country's 2006 GDP. Too often, sanitation solutions fail to address the full problem due to the complexity of constraints imposed by the environment, available technology options, and the many different stakeholders involved. Several frameworks have been established to distill possible solution paths, such as technoeconomic analysis and multi-criteria analysis (MCA). However, technoeconomic analyses alone do not consider the multitude of other facets that contribute to sustainable sanitation, and MCAs are often very context-specific, non-quantitative, and used primarily for comparative purposes. The SaNI framework enables analysis of cost of sanitation systems vs. population density to yield underserved populations and perform an MCA-like analysis to determine whether other, non-monetary, sustainable sanitation requirements are met. A case study applying this framework to the Indian context identifies population densities between 10,000 and 23,000 people/km^2 as regions where current technologies fail to meet cost requirements. The test case demonstrates quantitatively that septic tanks, a ubiquitous on-site sanitation method, are likely to be unsuitable for people with lower-than-average available land areas and abilities to pay. By quantifying the deficiencies of current sanitation technologies, the proposed framework can guide the development of the next generation of truly sustainable solutions.

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Title: Associate Professor of Mechanical Engineering

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Chapter 1

Introduction

Worldwide, over two billion people lack access to at least basic sanitation [1]. The World Health Organization (WHO) identifies India as a key country in need of safely-managed sanitation. Although India's Swachh Bharat Mission reduced open defecation by building over 100,000,000 toilets, making sanitation sustainable remains a significant challenge [2, 3, 4]. There is no "one-size-fits-all" solution for the sanitation difficulties that remain in such a widely-variable environment as India. The inter-connected challenges of economics, technology, culture, and politics, are often considered separately which hinders the solution creation process [5].

Technoeconomic analyses are very effective at considering the financial feasibility of sanitation systems. High-level studies performed by the World Bank are excellent at exploring the in-depth feasibility of a class of solutions at the country-level [6, 7]. Stantec (2019) presents a detailed model-based analysis of eight different systems through the lens of costs to a municipality [8]. Daudey (2018) performs a comparative analysis on the life cycle costs of complete sanitation systems to reveal the cheapest-per-capita solutions [9]. These financial analyses are effective for identifying cost-related gaps in sanitation technologies and infrastructure but other aspects of sustainability must also be considered. Some technoeconomic analyses, like Kamble *et al.* (2019) extend their framework to one or more sustainability metrics through the use of life cycle analysis (LCA) [10]. Although these LCA-type analyses are capable of analyzing the cost and cost-adjacent facets of sanitation, sustainable sanitation often requires parsing disparate types of information.

Multi-criteria analyses (MCA) are effective multi-faceted approaches for parsing such disparate information. Hellström *et al.* (2004) propose a framework for such an analysis while Lennartsson *et al.* (2009), Salisbury *et al.* (2018), and Vidal *et al.* (2019) use similar frameworks to compare the sustainability of current sanitation systems to each other within a particular context [11, 12, 13, 14]. Bassan *et al.* (2015) is the first known case of a quantitative MCA used in sanitation to judge deficiencies in management and planning [15]. These analyses are able to identify an optimal solution but, with the exception of the analysis done in Bassan *et al.* (2015), are unable to elucidate whether these sanitation solutions are "good enough" to meet the needs of the populations they serve. Identification of the gaps between current sanitation system performance and the requirements of the people most in need would lead to an effective prioritization path forward for technology and solution developers.

We seek a generalizable, quantitative framework capable of identifying these gaps. This framework should be context-specific enough to elucidate meaningful deficiencies while still being general enough to not require a detailed case study for each city considered. Using an MCA-like approach, the Sanitation Needs and Innovation (SaNI) framework uses technoeconomic analysis of common sanitation solutions, as functions of population density, to identify underserved populations. It then uses estimates of technology performance along multiple quantitative sustainability criteria to assess whether the needs of the identified population are met. This allows identification – and quantification – of gaps between the performance of the most commonly-implemented sanitation systems and requirements of this fairly well-defined – yet still general – underserved market segment.

Chapter 2

Presentation of the SaNI framework

The goal of this work is to create a framework capable of identifying how existing technologies do not meet key, quantitative needs of high-risk Indian populations. The incredible cultural and geographical diversity of India necessitates a coarse analysis of which populations are most able to benefit from improved sanitation. To do this, the framework, shown in Fig. 2-1, first identifies an underserved population based on the financial feasibility of existing sanitation systems. This context is then further defined by examining what types of communities contain these populations and what business models are most prevalent within those institutional capacities.

Within this context, sustainable sanitation criteria can be selected from a list of candidate criteria proposed by other multi-criteria analyses like Lennartsson *et al.* (2009) and Salisbury *et al.* (2018) [12, 13]. Because this framework is based on quantifying needs, only quantifiable and measurable sustainable sanitation criteria are selected. Context-specific requirements are then estimated by aggregating expert opinion, academic publications, grey literature, and field observations. Technology performance estimation is performed in a similar fashion by taking a subset of existing sanitation technology systems for evaluation, breaking them down to the sub-system level (where manufacturer specifications are available), and summing system component contributions to obtain total system performance. Comparison of these context-specific requirements to the estimated sanitation technology performance yields quantitative gaps between these two quantities along each chosen sustainable sanitation criterion.

2.1 Context definition

For the purposes of the initial coarse scoping analysis, we focus on using simple **sanitation system scaling relationships** to evaluate the economic feasibility of sanitation as a function of population density. This high-level technoeconomic analysis yields **underserved population densities** by modeling archetypal sanitation technology systems, for example, sewered conveyance to centralized treatment or completely on-site sanitation.

Dalberg Advisors (2018) identified that the overall feasibility of sanitation systems relies primarily on four variables (population, topography, aridity, and enabling ecosystem) of which population is the most important [16]. In the SaNI framework, we identify high risk populations by their population density rather than total population. Population density, total population and catchment area are all popular coarse ways of describing cities, towns and villages. Since processes like treatment are easy to think of in terms of their capacity, which is driven by the total population of the service area, a popular choice for executing a technoeconomic analysis is using population as the primary independent variable. A detailed analysis done by Stantec (2019) uses total population in this way but simulates an average population density that changes with population based on the city classes defined by the Central Public Health and Environmental Engineering Organisation (CPHEEO) [8]. This approach is effective if you consider the city to be homogenous but it is often the case that a single sanitation system is not uniformly economical over the whole city. For example, many Indian cities with sewerage have FSM toward the outskirts [17].

If a city is considered as an average, uniform population density, it is modeled as in Fig. 2-2 (left) where the total population is the volume of the cylinder. Inspired by Bettencourt *et al.* (2013), we instead consider the same city, but modeled as exponentially decreasing population density with distance from the city center (Fig. 2-2, right). In this case the densest parts of the city are near the center but each

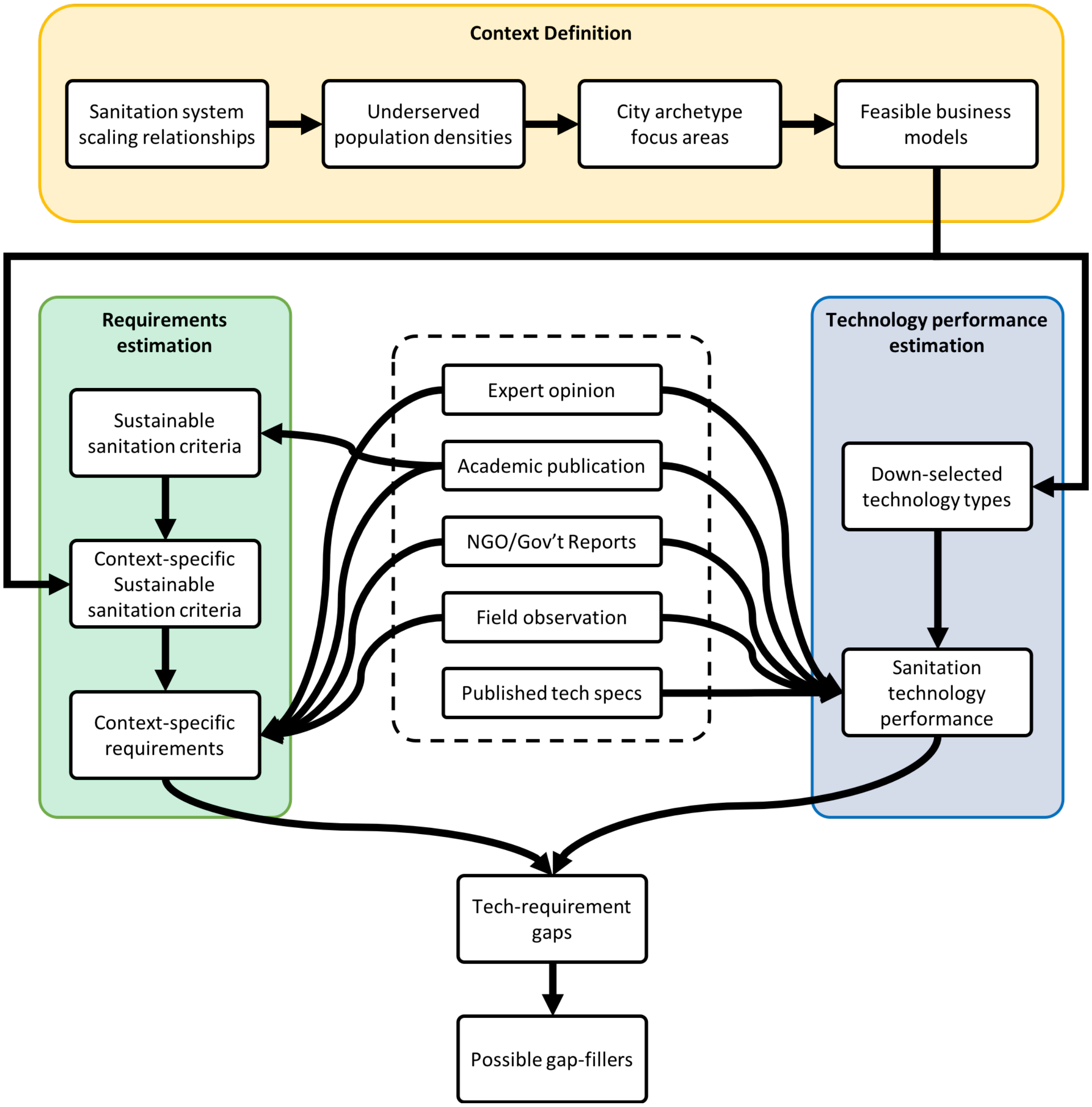


Figure 2-1: Process diagram of the SaNI framework for determining gaps between sanitation technology performance and the requirements of context-specific sustainable sanitation. The context definition subsection identifies an underserved subset of Indian communities using technoeconomic analysis. The requirements estimation subsection synthesizes disparate sources of information to yield context-specific requirements. The technology performance estimation subsection uses similar types of information sources to quantify sanitation technology performance.

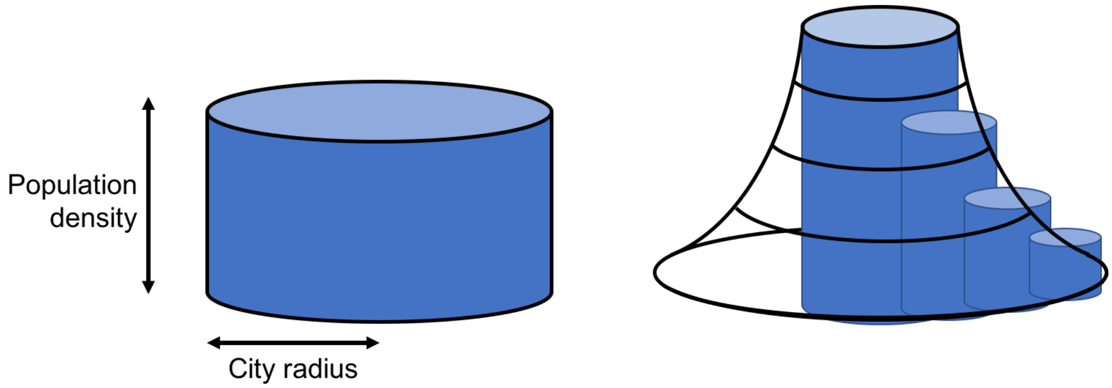


Figure 2-2: (Left) a city modeled as an area with constant (average) population density. (Right) a city of the same area and population modeled as smaller, discrete chunks of constant density that decrease exponentially as distance from the city center increases. Our model considers these “neighborhood-sized” chunks instead of a full city.

neighborhood-sized step outward density decreases. These smaller, neighborhood-sized chunks of a particular density can occur near the edges of large cities, or the centers of small cities. Using population density as the primary independent variable in our analysis allows the results to be generalized to a range of city archetypes.

Once population densities with the greatest gaps between cost of sanitation and ability to finance it have been identified, city classes containing those densities are characterized by “city archetype” like those presented by Dalberg Advisors (2018) [16]. Each of these city archetypes will have differing institutional and infrastructural factors that affect the feasibility of certain sanitation solutions in them (i.e. existing infrastructure, end-user ability to pay, and institutional ability to secure capital). These factors will also affect which business/service models are feasible. The requirements specified and the system performance evaluated are done so through the chosen business model(s) and city archetypes.

2.2 Requirements estimation

While the context definition identifies a financial gap, sustainable sanitation requires much more than just economic feasibility. The goal of this subsection of the framework is to define measurable criteria along which a sanitation system should be evaluated and its corresponding requirements for sustainability. Salisbury *et al.* (2018) and Lennartsson *et al.* (2009) present a compendious list of such criteria and factors that may affect their relevance to certain contexts[13, 12]. To clearly identify a sanitation gap, our analysis focuses on quantitative metrics of sustainability. Furthermore, quantitative metrics should also be measurable and data available. Using our context definition and understanding of the city archetypes, we are also able to filter out metrics that are always met in the chosen context. For example, it may be that energy use is a quantitative, measurable criterion for sustainable sanitation but grid power is widely and consistently available in a city of the chosen archetype; thus, lack of electricity is extremely unlikely to cause the sanitation system to fail. It should be noted that this filtering process removes many important factors of successful, sustainable sanitation that are hard to quantify or difficult to measure. Because of this, criteria and requirements presented in this framework are necessary, but not sufficient for sustainable sanitation.

Household water usage is a key constraint in sustainable sanitation systems - especially as water stress becomes greater [18]. This requirement could be thought of as a sustainability metric where the system boundary is drawn at the water table (requirement based on water recharge rate) or where system boundary is drawn at the municipal level (requirement based on supply). Basing the requirement on groundwater recharge rate would be a better absolute maximum in terms of environmental sustainability but basing it on supply capacity takes economic water scarcity into account as well. A more complete measure of this requirement would be the minimum of these two definitions. Due to lack of available high-detail groundwater recharge rates, our estimation uses the municipal level water availability minus drinking water provision to calculate an absolute maximum on water per person per unit time.

Household land usage is a prime determinant of on-site sanitation feasibility. In this case, we examine the ability for OSS to exist on the land allocated to the household (owned or rented). The area must be accessible, which means that land with a structure on it is assumed off-limits. This requirement is estimated based on ability rather than willingness since we were unable to quantify the amount of available land a household is willing to allocate for sanitation.

Capital cost is important for determining the community-scale affordability of the system. Regardless of how the systems are financed, each community has a capacity to acquire capital for sanitation. In India, capital cost is often financed externally as a lump sum (from the central government or a non-governmental organization (NGO)). Our estimation uses central government grant history to municipalities to define this requirement.

Annual cost is important for the financial sustainability of the system. In many cases, the annual costs that are paid for the upkeep of the system ultimately come from the citizens it serves. Whether it is a direct payment (sanitation tax), or municipality-sponsored (cross subsidized), the end-users are paying ([6]. Willingness to pay (WTP) is a function of what end-users are paying for and perceived value gained, so this metric is highly variable across different financing models ([19]. Instead, our analysis considers maximum ability to pay by examining household expenditure.

End-user participation is a requirement based on how much physical labor end-users will tolerate for sanitation. People will tolerate some actions (such as routine cleaning) at some frequency but not others (like hauling treated compost). The end-user participation metric is the product of the work the end-user does (energy measured in kJ) for sanitation normalized per time per person. We estimate this requirement based on willingness, not physical ability.

Smell to end-user is a requirement based on ensuring the usability of a system. Smell is often cited as one of the main reasons for not using a toilet [20, 21]. If a user does not opt to use the system, it does not matter how "sustainable" it is. It does not achieve its goal.

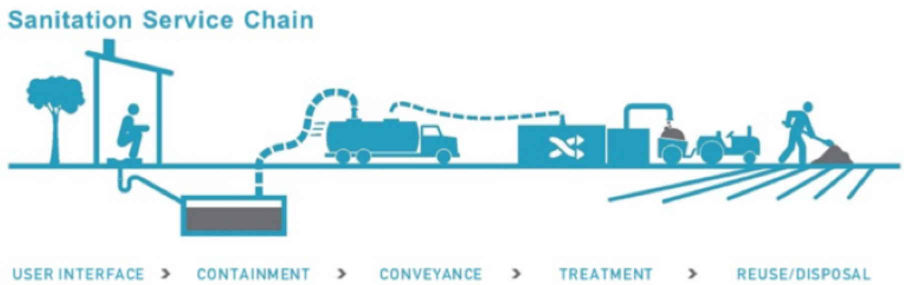
2.3 Technology performance estimation

This framework does not require that a particular set of sanitation technology systems be considered. As long as the performance of the system can be quantified, it is applicable within this framework. This makes analysis of widely-used, experimental, and theoretical systems all possible. Systems that are feasible for the underserved context identified should be selected for analysis. Much like the requirements, technology performance is estimated from the aggregation of the same types of published sources, field observation and technical specifications of sanitation systems and system components. Data sources vary widely depending on the performance criterion being estimated and the system it is being estimated for. Frequently, it is convenient to split up systems or sub-systems into smaller components. Tilley (2014) provides an excellent framework for considering the linking of sanitation sub-components. However, thinking about sanitation components as defined by Tilley (2014) is difficult when using real data on integrated systems like treatment plants [20]. These plants are often comprised of several different treatment subsystems, all using different technologies appropriate for that stage of the process. For example, if data on capital cost of a full treatment plant is available, and that plant uses three different treatment technologies, it is hard to attribute cost to each of these subsystems. This precise process for how to approximate this attribution is described in more detail in Chapter 4.

Chapter 3

Identifying a sanitation service gap in India

To identify potential gap in sanitation service, we used the framework to perform a technoeconomic analysis of common sanitation systems. This analysis determined which types of Indian population centers are likely to be underserved by modeling equivalent annual cost of three common sanitation systems, as a function of population density, and comparing them to consumer willingness and ability to pay. These full systems are each broken down into the five main components of the generalized sanitation value chain: user interface, containment, conveyance, treatment and reuse/disposal, as defined by Tilley *et al.* (2014) [20]. The three systems used in the analysis were: (1) sewer-based, centralized municipal sanitation; (2) on-site sanitation to centralized treatment (faecal sludge management, or FSM); and (3) dual pit latrine on-site sanitation (OSS) (Fig. 3). These three solutions were chosen for evaluation because they represent different balances between household and municipal infrastructural responsibility. In OSS, the household is primarily (or solely) responsible for the system, while in sewer-based, centralized treatment the municipality is primarily responsible for the system infrastructure and maintaining service. The FSM-based system represents a middle-ground of shared responsibility between these two solutions. This responsibility is apparent in the components one could expect to see in each of these model systems (tabular in Fig. 3-1). In OSS, since treatment is done on-



On-site sanitation (Usually called OSS)	Squat pans*	Dual pit latrine	N/A	(On-site)	Fertilizer
On-site storage to centralized treatment (Usually called FSM)	Squat pans*	Septic tank	Vacuum truck	Centralized treatment**	Liquid discharge / Compost
Sewer-based to centralized treatment	Squat pans*	N/A	Sewer system	Centralized treatment**	Liquid discharge / Compost

Figure 3-1: The sanitation service chain. While this graphic depicts a typical non-sewered system, the five processes are generally representative of all physical components of a sanitation system. Waste is captured via user interface at the household level, contained until it is conveyed to treatment where it is reused or disposed of. Three complete sanitation systems of different scale are listed with their common components. Adapted from "Sanitation Value Chain" by the Bill and Melinda Gates Foundation (BMGF) licensed under CC BY 2.0.
*These systems are user interface-agnostic but our model uses the ubiquitous squat pans
**Many treatment options exist. Often, these are combinations of technologies

site there is no conveyance or reliance on central treatment. In both FSM-based and sewer-based systems the treatment options are widely-varied and a typical treatment system is made of many treatment steps for both liquids and solids. In sewer-based systems, sewage is conveyed directly from the user interface to the treatment plant so household-side containment is not necessary.

3.1 Construction of the technoeconomic model

To capture the scaling relationships between these three systems, we modeled capital and annual costs dependent on four major types of population density-dependent cost drivers: treatment cost, network cost, household unit cost, and land cost. Table 3.1 shows how they apply to each of the three systems, their associated equations, and

Table 3.1: Cost drivers of the technoeconomic model and their associated equations.

	Treatment cost		Network cost	Household unit cost	Land cost
	Volume	Cost			
Sewer-based	***Eq. 3.1***: CPHEEO (1993) Data: CPHEEO (1993)	***Eq. 3.2:*** Best fit Data: Pannirselvam (2015)	***Eq. 3.4***: Best fit Data: Balalji (2015)		
FSM-based	***Eq. 3.3:*** Tayler (2018) Data: CPHEEO (1993)	***Eq. 3.2:*** Best fit Data: NIUA (2019)	***Eq. 3.5*** Data: Kone (2012), CPHEEO (1993)	Data: Ganesan (2017)	***Eq. 3.6***: Bertaud (2015) Data: Chakravorty (2013), GOI Census (2011)
Dual pit latrine				Data: Ulrich (2016)	***Eq. 3.6:*** Bertaud (2015) Data: Chakravorty (2013), GOI Census (2011)

data sources from which the relationships were derived. The Central Public Health & Environmental Engineering Organization (CPHEEO) is a technical wing of Ministry of Housing and Urban Affairs, Government of India, and publishes guidelines on the engineering of sewerage and sewage treatment systems.

In each case, it was assumed that population is uniformly distributed over a neighborhood-sized area, rather than a city-sized one (as described in Fig. 3-1). Furthermore, each system considered was assumed to be the only sanitation system implemented and reaches 100% of households. Each cost driver is described in turn below. For each cost driver, V denotes volume delivered to a treatment plant, P denotes the total population served, C denotes capital cost, and A denotes an annual cost.

Treatment cost includes both the capital and annual costs incurred by treating sewage or septage at a centralized treatment plant. Capital costs include the construction costs of the plant, and annual costs are inclusive of operation and maintenance costs. Both of these costs scale primarily with the volume treated. For the sewage treatment plant (STP), our model assumes that volume delivered to the treatment plant is given by CPHEEO (1993) [22],

$$V = 0.8V_{supply}P, \tag{3.1}$$

and assumes that V_{supply} is 100 L/capita/day for a piped domestic water supply as per CPHEEO (2013) [23]. Treatment plant capital cost was regressed from data in

Pannirselvam (2015) and is given by

$$C_{treat} = VaP^b, \tag{3.2}$$

where a and b are regression constants [24]. The plants included in the dataset are all in Tamil Nadu and based on the activated sludge process, which is common in India. Annual cost for the STP is estimated to be 10% of the built system's capital cost based on Faecal Sludge Treatment Plant (FSTP) annual and capital cost data from NIUA (2019) [25]. While this estimate is not for the same type of treatment plant, it is consistent with annual cost to capital cost ratios of centralized sewage treatment infrastructure [26].

For septic tanks, the volume of liquid waste produced is estimated following Tayler (2018) as

$$V = \frac{N v_t c_t}{T}, \tag{3.3}$$

where V is the volume delivered to the treatment plant in m^3/year, N is the number of pits and tanks in the service area, v_t is the average tank capacity in m^3, c_t is the proportion of pits that are regularly desludged (assumed to be 1), and T is the average interval between tank desludging in years [27]. The septic tank sizing, v_t, was calculated assuming only discharge from the water closet (excluding domestic wastewater) using septic tank sizing guidance from CPHEEO (1993). This analysis assumes T is 3 years as recommended in CPHEEO (1993) [22].

Septage (faecal sludge) treatment cost is regressed from a limited set of four full liquids and solids treatment FSTPs across India (NIUA 2019) [25]. The cost relationship between capital cost and annual cost follows the same form as Eq. 3.2 with different regression constants.

Network cost includes both the capital and annual costs of conveyance from the household to the treatment plant. Capital cost of the sewer network is defined primarily by the amount of linear sewer length and associated pumping stations the network requires. This model assumes service areas do not have significant elevation change. Downward slope to the STP decreases the number of pumping stations required while an upward slope increases it. Given these two competing factors, and lacking any topographical specificity, a flat service area is assumed to be a good average case. Our model used the constructed costs of 33 sewer networks in Tamil Nadu from Balaji 2015 to regress the following relationship between population served and total sewer network capital cost [28],

$$C_{network} = aP + b. \tag{3.4}$$

Intuitively, both population and land area should be correlated with sewer network capital cost but there was no significant correlation in this dataset (see supplemental information for details). Annual cost required to upkeep the network was taken to be approximately 5% of the capital cost in the case of a conventional sewer network [26]. This exact percentage will be different for India due to different labor and material costs, but the conveyance technology is the same, so it is assumed suitable for the coarse analysis performed here.

The FSM network cost is driven by the number of trucks and operators required to keep up conveyance. The relationship derived from values presented in Chowdry *et al.* (2012) yields

$$C_{network} = \frac{C_{truck}}{k} P, \tag{3.5}$$

where k is a service population of 25,000 people per truck, assuming Indian emptying frequencies, and a standard 2.5 – 5 m^3 capacity truck. C_{truck} is the unit cost of a truck ($10,000 USD per truck) [29]. Annual cost is driven by operator wages, maintenance, and other fees. Assuming profit margin is 30% of the total emptying fee for an on-demand desludging schedule ([29]), an average cost of 1000 INR per desludging ([30]) yields an average cost of 700 INR per desludging. Using the 3-year desludging frequency recommended in CPHEEO (1993), the total annual cost is the total number of households multiplied by desludging frequency and cost per desludging [22]. These first-order scaling relationships are limited by the lack of consideration given to geography- and city-specific factors. However, they are sufficient to highlight cost trends across a range of population densities and identify high-level coverage gaps.

Household unit cost is the cost of household capture and containment systems such as a pit latrine. Ganesan *et al.* (2017) reports a range of 25,000 – 40,000 INR per constructed septic tank across eight different states, which is consistent with the authors' field observations in Maharashtra and Gujarat [31]. Unit cost of a pit latrine is around $184 USD but depends on the cost of locally-available materials [32]. The cost of the plumbing of a water closet is assumed to be included in the network cost and the cost of the user interface is assumed to be negligible.

Land cost of the system is only the cost of land used for the on-site units. Since municipalities often already have land procured or tend to put treatment facilities on undesirable plots, land usage of municipal systems is not considered. In this model, land cost is accounted for in one of two ways: (1) as a soft constraint where it is added to the total cost of the system or, (2) as a hard constraint where it is not added to total cost but systems are not modeled above population densities that make them infeasible. This infeasibility is based on the ability for an OSS to fit in the total land area allocated to the household minus the area of the dwelling. The equation for the cost of land used in the soft constraint is derived from the land cost and population density relationships given by Bertaud and Malpezzi (2003) with data from Chakravorty (2013) and the Government of India census (2011) [33, 34, 35]. The resultant land cost relationship is

$$C_{land} = aD^b, \tag{3.6}$$

where D is the population density and a and b are regression constants. For more information, see the supplemental information.

When considering the overall cost of a system with several hardware components of different service lives, it is common to normalize them by amortization [8, 36]. An equivalent annual cost of each hardware subsystem considered in this analysis is calculated using

$$EAC = C\frac{(1+i)^n * i}{(1+i)^n - 1} + A, \tag{3.7}$$

where EAC is the equivalent annual cost of the amortized system, C is its capital cost, n is its service life, i is the real interest rate, and A is the annual cost (including maintenance, operations, etc.). The real interest rate, i, is an adjusted interest rate equal to a nominal, reported interest rate minus inflation. In our analysis, we assumed this real interest rate is 5%.

To elucidate possible financial gaps, cost of sanitation was compared to the end-user's willingness to pay. Similar to the requirements discussed in Chapter 2, this point of comparison could be quantified using either ability or willingness to pay. Due to the lack of generalizable population density-correlated willingness to pay data, we used expenditure as a proxy for ability to pay. Household expenditure is used as an estimate of true ability to pay instead of income to discount income that goes toward savings. Household expenditure data is from the Indian National Sample Survey Organisation's NSS 69$^{\text{th}}$ round [37]. Data from the NSS 72$^{\text{nd}}$ round further breaks down expenditures showing that urban households spend an average of 0.21% of their budget on "sewage disposal & sanitation" [38]. Because this amount consumers currently pay may not be an accurate maximum for what they are willing to pay, for the remainder of the analysis, we considered the hypothetical that consumers are willing to pay up to 5% of the total expenditure (though it is a high upper bound).

A successful sanitation system must "ensure access to water and sanitation for all" [39]. In the context of this economic analysis, it means that a solution should be financially feasible for every household, not just those wealthy enough to access services. To represent this equity requirement, household expenditures are grouped into population density ranges with a distribution of expenditures for each range. In an effort to make our analysis a reflection of this equity goal, our "ability to pay" is specified by the 5$^{\text{th}}$ percentile household of each of these bins. For more information, see the supplemental information.

3.2 The missing middle in sanitation technologies

The equivalent annual costs of each sanitation technology system were compared to consumer ability to pay to yield population densities where sanitation costs may be greater than the consumer's willingness to pay. Fig. 3-2 illustrates the cost of the three modeled sanitation systems as functions of population density. Unmet sanitation needs occur where the least-cost solution exceeds the consumer's willingness to pay, characterized by the green line. The most cost feasible option of these three is the dual pit latrine, which remains a viable option up to population densities of 10,000 people per km^2, where it becomes infeasible to build due to the available land per household. Household septic tanks become equally infeasible for similar reasons above 18,000 people per km^2. This means that at very high population densities, the only feasible solution of these three classes is the sewer-based system. This line does decrease with population density, though it is still more expensive than the others overall.

Land cost modeled (included as dashed lines in Fig. 3-2) is not explicitly paid by households but is representative of the opportunity cost of what could have otherwise been done with the land. This method of accounting for land is not financially accurate (no Indian households pay such an inflated price for OSS since they already have the land) but is illustrative the tradeoff a household must make when considering what to do with the land area they have.

Compared to the fully model-based approach taken by Stantec 2019, our model outputs higher costs for both the septic tank-based FSM and sewer-based systems (Dual pit latrines were not modeled in their analysis) [8]. For the septic tank-based system, this cost difference can be attributed primarily to the difference in the system boundary considered. Our system factors in the household costs of user interface and containment while the Stantec 2019 approach excludes these costs for the purposes of focusing on costs to a municipality. Stantec's model is a least-cost scenario that does not include secondary site infrastructure at the STP or FSTP such as roads, office, and other costs not directly associated with the physical treatment process. Our costing

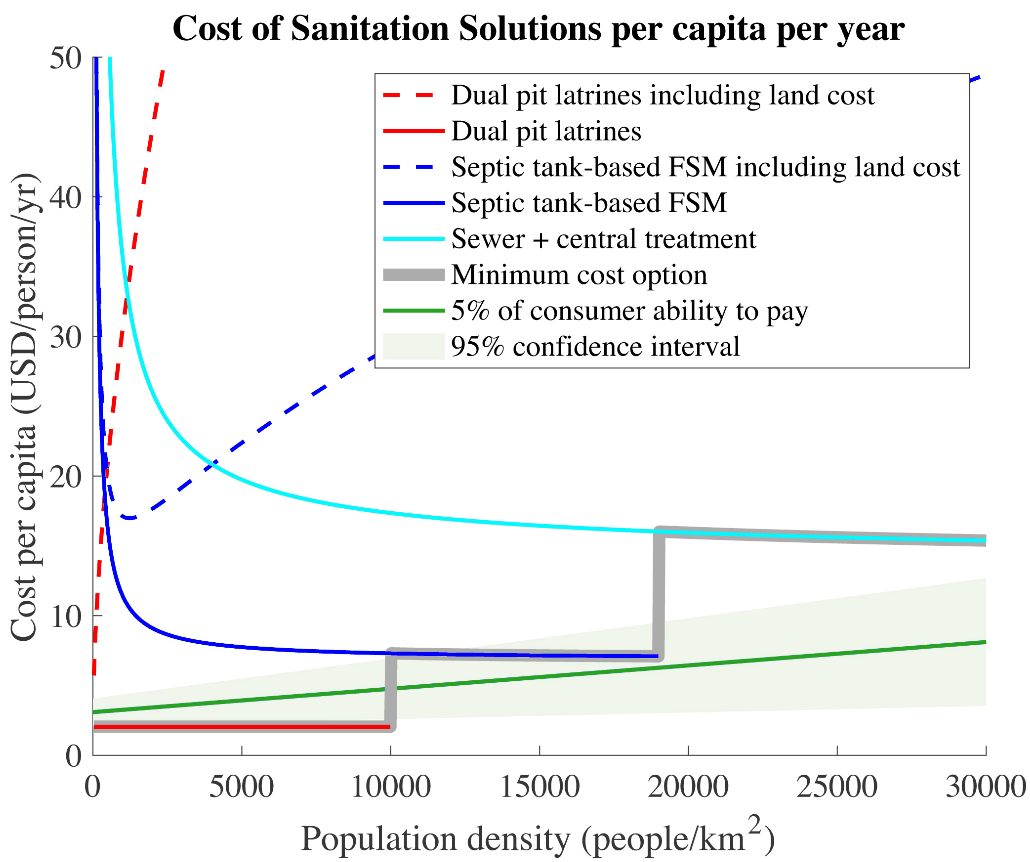


Figure 3-2: The total equivalent annual cost of the three modeled sanitation systems as a function of population density. Pit latrines are an inexpensive option that is infeasible at population densities greater than 10000. Septic tanks are the second least costly option but are also infeasible at high population densities. Willingness to pay is plotted based on 5% of a 5^{th} percentile person's total yearly expenditure. Dotted lines are inclusive of land costs of the household part of the system.

process implicitly includes costs such as these because our models were regressed from real data on built costs that do include this secondary infrastructure. Stantec estimates that these secondary infrastructure costs could be up to an additional 50 - 100% of total capital cost [8]. This is consistent with the discrepancy between their and our modeled results. It should also be noted that the sewer networks from Balaji 2015 are all smaller sewers of up to about 3,500 people/km^2 [28]. The regressed model was confirmed to correlate with costs from the Tamil Nadu Water Supply and Drainage (TWAD) Board for populations up to about 10,000 people/km^2. Beyond that, our model extrapolates the established trend in sewer network cost with increasing population served.

Because our analysis is in the generalized population density space, these high-risk population densities are not cities themselves but are neighborhoods that can occur in many city types. These regions in the 10,000+ people/km^2 range fit within two largest city archetypes proposed by the Sanitation Technology Program (STeP): the "Sprawling Megacity" and "Rising Metro" [16].

These city archetypes are classified by total population, existing sewerage, ability to secure financial capital, topography, and whether the city/town has a special sanitation-related focus. For demonstration of the framework, we focus on one sample case in the "Rising Metro" city archetype. Cities of this type have population between 1 and 8 million people, more than 40% existing sewerage, and an expanding periphery, which is likely to remain unsewered for the near future. The ability to secure finance in these cities is high due to their high total population.

These cities are predominantly funded by central government and donor-led business models which enables sanitation systems that would otherwise be financially infeasible, such as in the JNNURM or AMRUT missions [40, 41]. Because of its reliance on external charitable funding, this business model is not sustainable, nor is it scalable [42]. A commonly-implemented version of this model utilizes these donated funds to construct, but not operate the sanitation system. Once constructed, business operations of the system could be managed by the municipality itself or handed off to a private partner [30]. For the remainder of the presented analysis using the

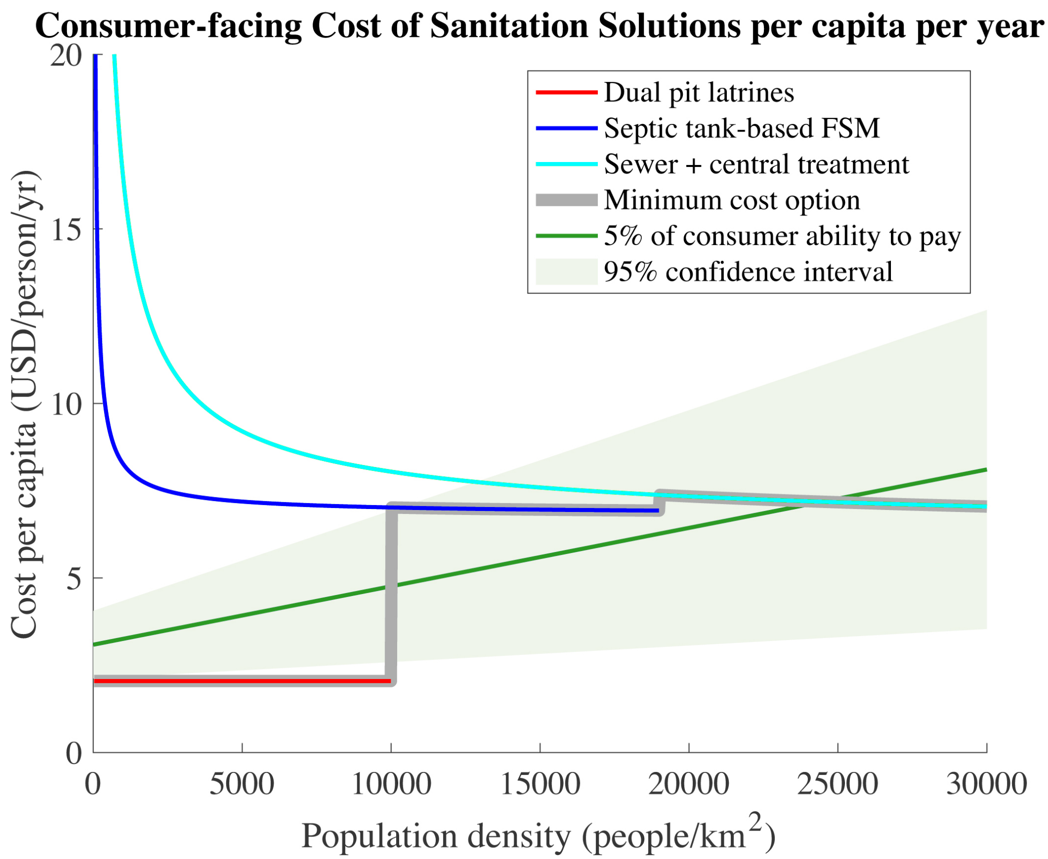


Figure 3-3: Consumer-facing costs of the three modeled sanitation systems assuming capital cost of centralized infrastructure is grant-funded (not passed on to the consumer). Willingness to pay is plotted based on 5% of a 5$^{\text{th}}$ percentile person's total yearly expenditure.

SaNI framework, we assume this most prevalent business model: capital costs of the centralized infrastructure are grant-funded and operational expenses are recouped through consumer expenditure. Fig. 3-3 shows the same population density space as figure 3-2, but with only the consumer-facing costs of the systems given the assumed business model.

Even with grant-funded capital, consumer costs are still high enough to produce unmet need. Since the costs of these sanitation systems are much higher than the 0.21% of household expenditure that people reported to pay for sanitation services (NSSO 2016) we can conclude that sanitation services operate with significant subsidies [38]. Cross subsidy, commonly through property tax, is a popular method for financing this cost gap (World Bank 2016; HPEC 2011). It is also possible that consumers are willing to pay more than they are currently paying. In Fig. 5, the hypothetical 5% of consumer expenditure shows that at this (very high) rate, the median consumer is able to cover their share of the sanitation cost but the 5^{th} percentile person is not. These 5^{th} percentile households living between 10,000 people/km^2 and about 24,000 people/km^2 inhabit a gap in sanitation service. These households at the upper-medium population densities are at higher risk for having no cost-feasible, equitable sanitation solution.

Using the SaNI framework provided a simple way to elucidate this market gap and quantify why it exists. Each piece that went into the framework aligns with what is expected: on-site sanitation is infeasible when land becomes scarce, centralized systems get cheaper per capita as they get larger, and people are not willing to pay enough to cover the complete costs of sanitation. With these pieces quantitatively defined and combined – even with simple scaling relationships – there are clear gaps between what people require of the system and what the system requires of them.

Chapter 4

Test case: Evaluation of an FSM-based system

The goal of this analysis was to determine the performance gap between what current sanitation solutions can provide and what the needs of the "Rising Metro" city, contingent to a donor-sponsored business model are. Given the high-risk context of low-income households at the population densities of 10,000 people/km^2 to 24,000 people/km^2 and the sustainable sanitation criteria chosen in the Chapter 2, the requirements for sanitation technology performance could be estimated. To illustrate how the SaNI framework is used to evaluate candidate solutions against requirements, we analyze an FSM-based system within the "Rising Metro" city.

4.1 Requirements estimation

Each requirement estimate belongs to one of two categories: physical possibility or realistic capability. Physical possibility indicates a fundamental resource constraint. For example, in water usage, the absolute maximum quantity that may be available for sanitation is the volume of water extracted minus the volume of drinking water consumed. While this estimate is unrealistic due to uses other than drinking or sanitation, it is still a useful upper-bound. A more accurate, albeit harder to measure bound is one specified by realistic capability. For water usage, this would likely take the form of surveying constituents of the target populations to quantify how much water they would be willing to expend for sanitation. This is the effect of ability versus willingness to expend a resource for sanitation. Notably, willingness can be changed with improved service, marketing or education (like in community-led total sanitation or CLTS) while ability cannot. Whenever possible, we try to capture willingness in our requirements but when infeasible, we instead capture ability.

The **household water usage** requirement is estimated assuming water supply capacity is the limiting factor (not ground water recharge rate). Using the reasoning put forth in the Chapter 2, we find "Rising Metro" archetype cities supply between 70 and 135 L per capita per day (LPCD) [35]. According to Shaban (2007), these cities use 15.9% to 25.7% of total water use for sanitation [43]. Assuming the remainder of the supplied water must be used for higher-value uses, this puts an upper bound on how much water could possibly be used for sanitation.

The **household land usage** requirement is estimated using the assumptions and reasoning in the Chapter 2 section. Data from the NSS 69$^{\mathrm{th}}$ round and 2011 Census show the 5$^{\mathrm{th}}$ percentile household in the high-risk population density range has up to 2.25 m^2 per person of non-dwelling land that could possibly house an on-site sanitation system. Many of the households do not have any non-dwelling land which is reflective of the constraints of the high-density urban environment.

The **capital cost** requirement for this context is the average capital local governments were able to secure from the central government for sanitation projects. The average and 75$^{\mathrm{th}}$ percentile are used as "maximum bounds" since cities with a special sanitation focus are shown to be outliers. If an average city of this type wants to build sanitation infrastructure, there is a high probability that it will be able to secure an average amount, but it is far from guaranteed that every city could reach the high points that the outliers can.

The **annual cost** requirement is estimated as outlined in the Chapter 2. The business model assumed relies on the citizens financing this part of the system so it is directly-comparable to the ability to pay. This quantification is done similarly to the willingness to pay, where household expenditure data are taken from the NSS

69th round. Similarly, this annual cost requirement is imposed by the 5th percentile household expenditure for population densities that span the high-risk city archetype.

The **level of end-user participation** requirement is estimated based on data gathered on willingness to participate in the household recycling process, which is a process similar in nature to the process of household sanitation maintenance tasks [44]. This provides an amount of time the task takes and the frequency of the task. Our analysis weights tasks differently by considering how strenuous they are. Human power expenditure for a wide variety of tasks is given in Ainsworth (1993) [45]. The product of power expenditure and time spent participating in maintenance of the system gives the physical work (in kJ) per person per year to keep the sanitation system functional.

The **end-user smell** does not have a resource constrained "physical limitation" on how much a system can smell, but we instead use published data on what smell level of certain "sanitation smells" users are willing to tolerate. In this case, the measured "sanitation smell" is Hydrogen Sulfide, H2S, chosen for its simple detectability [46]. According to the World Health Organization (2000), for H2S, 0.1 ppm is the threshold for avoiding annoyance over a prolonged, 24-hour exposure. The threshold for "substantial complaints about odour annoyance" is 0.05 ppm over a period of thirty minutes.

The six requirements of sustainable sanitation for the 5th percentile and median households in the "Rising Metro" city are summarized in Table 4.1.

4.2 Sanitation technology performance estimation

When evaluating potential sanitation solutions using the SaNI framework, it is assumed that all sanitation systems provide adequate protection of human and environmental health (high enough service level) and that systems are 100% functional and properly-maintained.

Technology performance estimation is done on the subsystem level. This is convenient because subsystems are often specified as single units (like the user interface

Table 4.1: Quantifiable requirements of sustainable sanitation in upper-middle population density Indian communities
*This low estimate requirement signifies that the 5th percentile household does not have any non-dwelling area

Criterion	**Indicator/unit**	**Requirement (low estimate)**	**Requirement (high estimate)**
Household Water usage	m^3/person/year	4	13
Household land usage	m^2/person	0.00*	2.25
Capital cost	USD/person	23.86	33.77
Annual cost	USD/person/year	0.15	5.50
Level of end-user participation	kJ/person/year	33.5	50.2
End-user smell	ppm H2S x 100	5	10

component). However, even when they are not (for example, when the total cost of a treatment plant is given but it contains multiple different technologies) approximate general cost breakdown percentages can be gleaned from built systems with an associated cost breakdown. We assume that full technology systems of the same type have a similar cost breakdown. This allows us to use the same percentages to estimate cost breakdowns for other built systems (from government tenders and other published figures) that only have total system costs. For the other, non-cost, system performance metrics we use the same process where data are available. When unavailable, we use the cost percentages as a proxy for the percentage-wise contributions of each subsystem to the total. This enables us to mix and match compatible subsystems to quickly explore the effects of many combinations of sanitation solutions.

4.3 Example results for an FSM-based system

The six requirements in Table 4.1 are plotted against the performance of an FSM-based system on a six-pointed radar plot (Fig. 4-1). An FSM-based system was used because it is the system closest to meeting the financial requirement of the three in

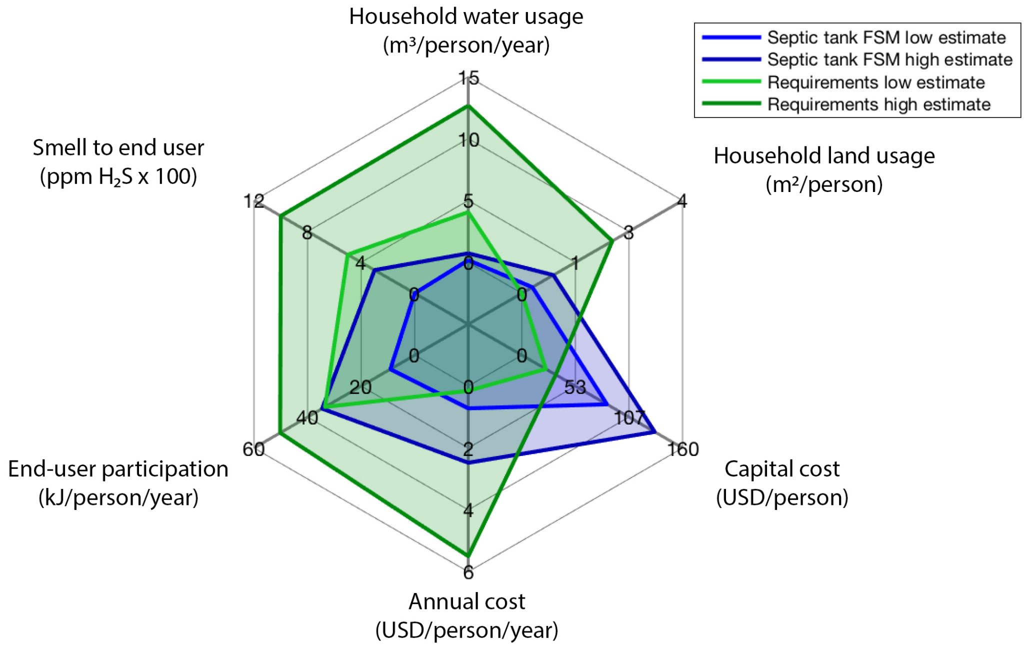


Figure 4-1: faecal sludge management-based sanitation system (blue) plotted against the requirements (green) of the "Rising Metro" city archetype. This system meets all requirements with the exception of the capital cost requirement.

the technoeconomic analysis. This graphical depiction allows us to easily gauge the performance of the technology system relative to the requirements along each of the criteria.

The FSM-based systems plotted in blue in Fig. 4-1 tend to satisfy the quantified sustainable sanitation requirements of the "Rising Metro" city archetype. When both the high and low performance estimates lie inside both of the requirement estimates, we can have high confidence that the requirement is met. Likewise, if both performance bounds lie outside the requirements, then the requirement is very likely not met. It is unsurprising that the solution violates at least one of the cost requirements (capital cost) since the cost of this sanitation technology was higher than willingness to pay in the techno-economic analysis.

The goal of this part of the SaNI framework is to determine what aspects of the chosen sanitation systems need to be improved, and by how much. A traditional MCA used to pick the best solution for a given context relies on weighing the criteria used for analysis. In this case, because the goal is sustainable, equitable sanitation, meeting every is necessary. It is therefore not useful to measure which are more important. They must all be met. However, because this analysis is quantitative, we are able to estimate how much a system would have to improve along the unsatisfied criteria to meet the requirements.

In this sample analysis, the lower limits of household land and annual cost are zero and nearly zero, respectively. From this, we can posit that septic tank-based FSM systems are largely feasible in the "Rising Metro" city (also evidenced by their existence) but present two challenges: (1) annual cost is still too high to meet ensure equitable service and (2) there is some fraction of the population (greater than 5%) that simply cannot have a system that takes up permanent area outside the household. We also see that the capital cost is higher than even the median person's willingness to pay. This is just one example of how the SaNI framework can be applied. One could imagine that if this same analysis was done on a sanitation system that was not as ubiquitous, different requirements may have been violated, therefore highlighting different areas of opportunity for improvement of that technology system. Furthermore, as long as requirements and sanitation technology performance can be quantified, they can be included in the gap analysis. The SaNI framework could also serve as a first-order feasibility assessment for solutions that have not yet been tested in the field.

Chapter 5

Discussion and implications

The SaNI framework is built to identify tangible ways to improve sanitation technology systems relative to the requirements imposed by a context of greatest financial need. Bassan (2015) presented a framework motivated by similar goals to uncover deficiencies on the management and operations side of sanitation systems [15]. The SaNI framework fills a comparable role but for the technologies themselves. This enables the identification of quantified ways in which sanitation technology systems can be improved to better-meet the needs of whichever underserved market segment is identified by the framework (in this case, upper-medium population densities in the "Rising Metro"). In the chosen sample case, our framework identifies that upper-medium scale population densities do not necessarily have access to sanitation that meets their financial needs. The quantitative performance-requirements analysis done for this underserved region found that an FSM-based example system falls short of meeting the land area, annual cost and capital cost requirements of households who have the least.

The SaNI framework accomplishes this by defining an underserved context based on population density, the prime driver of sanitation technology scaling. This way of segmenting the solution space is specific enough to use a multi-criteria-like approach, while being general enough to be applicable outside a single city. The simple process for estimating community requirements and sanitation system performance is capable of identifying non-financial deficiencies in these systems. This ultimately leads to areas of opportunity for technology development. This same framework could also be applied to theoretical sanitation solutions with hypothetical scenarios to serve as a first-order test for feasibility across a few necessary sustainability criteria.

One limitation of the framework is that it focuses on quantifiable sustainable sanitation criteria. There are likely many other less-quantifiable metrics that are equally, if not more, important for determining the overall sustainability of a system. System complexity is one such example of a metric that is not sufficiently quantifiable to be included in the framework as we present it here. It is often cited as a major factor in the successful operation of a system [47, 48]. The concept of system complexity encompasses the understanding that a system should rarely fail, be observable when it does, and be easy to fix. These criteria, among others, are difficult to quantify concisely. Bassan (2015) is a strong example of such an analysis for management and operations practices in wastewater and faecal sludge treatment. However, an analogous technical analysis, perhaps based on "failure modes and effects analysis" (FMEA), could identify – and quantify – how sanitation technologies can become easier to maintain and operate.

The filtering process used to generate the final list of sustainable sanitation criteria also presents a limitation of the analysis. Meeting quantitative requirements for sustainable sanitation does not necessarily mean a system is sustainable. Some non-quantitative considerations, removed by the filtering process, may render the system unsustainable. In a sustainable system, all criteria relevant to the identified context are necessary. This means any chosen subset of the full criteria list may rule out a solution or identify areas of opportunity. However, it is impossible to guarantee sustainability even if all known criteria are met. Some notable, non-quantitative criteria left out of the analysis are: equity (ability to adapt to needs of differing age, gender and income groups), resource recovery potential, nutrient removal/circularity, air emissions, physical suitability of the particular context and legal capacity [12]. These non-quantitative criteria need to be considered externally to the framework.

The technoeconomic analysis used to define the underserved context considers three main classes of sanitation solutions to represent the solutions space. Together, these chosen solutions cover a large portion of the solution space due to their use frequency, they do not account for all of the possible solutions [49]. Therefore, claims about any of the modeled trends being a least cost solution are limited to those three solutions and are not inclusive of novel technologies such as omni-processors. Despite the model's relative simplicity, the trends and results match those of the model in Stantec (2019) once difference in system boundary is accounted for.

The SaNI framework does not require that a particular set of sanitation technology systems be considered. As long as the performance of the system can be quantified, it is applicable within this framework. Even given its simplicity, this framework is an effective way to identify gaps between end-user requirements and sanitation technology system performance. The focus on analyzing neighborhood-sized chunks grouped by population density makes it capable of identifying sanitation deficiencies that occur in similar neighborhoods of otherwise dissimilar cities. These deficiencies are categorized by the sustainability criteria and quantified to elucidate actionable ways in which technologies can be improved.

Chapter 6

Conclusions

The SaNI framework presented in this work synthesizes disparate types of information to present insight into precisely how existing sanitation technologies do not meet a set of key, quantitative, community-scale needs based on sustainability criteria. It is capable of scaffolding the identification of underserved populations, and then quantifying potential unmet needs of that population along each of these sustainability criteria. This makes the SaNI framework a generalizable gap analysis tool.

As an example case, this work presents insight into precisely how FSM-based sanitation technology systems do not meet a set of key, quantitative needs of high-risk Indian population densities. We conclude that our technoeconomic analysis, based only on simple scaling relationships, can identify these high-risk population densities where cost of sanitation is lower than a consumer ability to pay that would constitute equitability.

In one test case of an FSM-based sanitation technology system, our framework finds that this commonly-implemented system does not inherently meet the requirements of equitable, sustainable sanitation for India. While the system does meet most requirements, it does not satisfy the capital cost requirement imposed by institutional capacity or the lower-bound household area and annual cost requirements. This means that the system, in its current form, is feasible on average, but is likely to be unsuitable for people with lower available land areas and lower abilities to pay.

Quantified deficiencies of current sanitation technologies are paramount to understanding what technology developers and researchers can contribute to making sustainable sanitation more equitable and attainable. Utilizing this framework to explore market gaps and candidate solutions could create a more coherent understanding of precisely how solutions fail to fill the human and institutional needs of sustainable sanitation.

Appendix A

Technoeconomic analysis supplemental information

Table A.1: Table of sewer network capital costs from Balaji *et al.* 2015. Data is supplemented by the city characteristics from the 2011 Government of India census. To explore possible correlation with area, sewerage coverage area is scaled to serve the entire city's population. This allows us to use the city's area as reported by the GoI census to see any correlation with sewer network area served. An "extrapolation ratio" calculated at right to show how much the city has been scaled. One city, Keeranur, was not considered because of a low extrapolation ratio possibly due to high growth between the 2011 census and the Balalji study.

Town name	Design quantity (MLD)	Street/Sewer length (km)	Design population	Total project cost (Rs. In Lakh)	City area (sq. km)	Total Population	Population density (people per sq. km)	Sewer length for full city (km)	Total cost for full city (Rs. In Lakh)	Total cost for full city (USD)	"Extrapolation ratio" (how different is their declared project size and the size of the city?)
Arumbavur	1.64	20.9	16400	2024	22.60	12467	552	15.89	1539	2000193	0.76
Kurumbalur	1.97	26.68	19700	2473	18.00	12420	690	16.82	1559	2026856	0.63
Annavasal	1.15	22.34	11500	1689	10.51	8906	847	17.30	1308	1700426	0.77
Karambakudi (Karambakkudi)	2.4	35.98	24000	3214	5.60	14626	2,612	21.93	1959	2546265	0.61
Keeranur	2.05	20.31	20500	2743	12.80	7200	563	7.13	963	1252414	0.35
Mettupalayam	0.9	21.67	9000	1328	8.84	7681	869	18.49	1133	1473386	0.85
Poovalur (Puvalur)	1.07	15.22	10700	1500	5.18	7905	1,526	11.24	1108	1440631	0.74
S. Kannanur	1.8	23.43	18000	2436	4.50	13073	2,905	17.02	1769	2299976	0.73
Thanthaiyangarpettai (Thathaiyangarpet)	1.77	26.99	17700	2458	9.50	12980	1,366	19.79	1803	2343293	0.73
Uppiliyapuram (Uppiliapuram)	0.9	17.16	9000	1556	7.16	7705	1,076	14.69	1332	1731742	0.86
Velankanni	1.7	23.44	17000	2618	5.50	11108	2,020	15.32	1711	2223822	0.65
Vaitheesvarankoil (Vaitheeswarankoil)	1	19.1	10000	2010	8.29	7676	926	14.66	1543	2005739	0.77
Manalmedu	1.2	21.51	12000	2105	15.50	9017	582	16.16	1582	2056252	0.75
Kivelur (Kilvelur)	1.3	22.16	13000	2050	4.00	8272	2,068	14.10	1304	1695760	0.64
Thattacheri (Tittacheri)	1.2	20.24	12000	1792	6.00	9245	1,541	15.59	1381	1794763	0.77
Needamangalam	1.2	14.76	12000	1600	2.62	9336	3,563	11.48	1245	1618240	0.78
Muthupettai (Muthupet)	2.9	37	29000	2867	12.80	21722	1,697	27.71	2147	2791726	0.75
Valangaiman	1.55	23	15500	2290	5.46	11754	2,153	17.44	1737	2257526	0.76
Koradacheri	0.9	11.45	9200	1435	3.90	6450	1,654	8.03	1006	1307878	0.70
Kodavasal	2.6	33	26000	3440	15.00	14639	976	18.58	1937	2517908	0.56
Madukur south (Madukkur)	2.6	29.34	26000	2927	5.75	16266	2,829	18.36	1831	2380529	0.63
Perumagalur	0.9	8.5	9000	1299	16.00	5604	350	5.29	809	1051497	0.62
Thirubuvanam (Thirupuvanam)	2.1	19.59	21000	2269	5.66	14989	2,648	13.98	1620	2105383	0.71
Vallam	2.3	38	23000	3185	7.60	16758	2,205	27.69	2321	3016804	0.73
Ammapettai	1.8	27.54	18000	2482	13.66	9677	708	14.81	1334	1734656	0.54
Melattur	1.15	20	11500	1749	25.50	8131	319	14.14	1237	1607605	0.71
Thiruvaiyaru	2.2	28.9	22000	2458	5.56	16164	2,907	21.23	1806	2347748	0.73
Melathirupanthuruthi (Melathiruppanthuruthi)	1	14.1	10000	1381	12.00	9074	756	12.79	1253	1629055	0.91

Left table from Balaji 2015
Supplemented data from 2011 Indian Census
Regressed from towns in Tamil Nadu

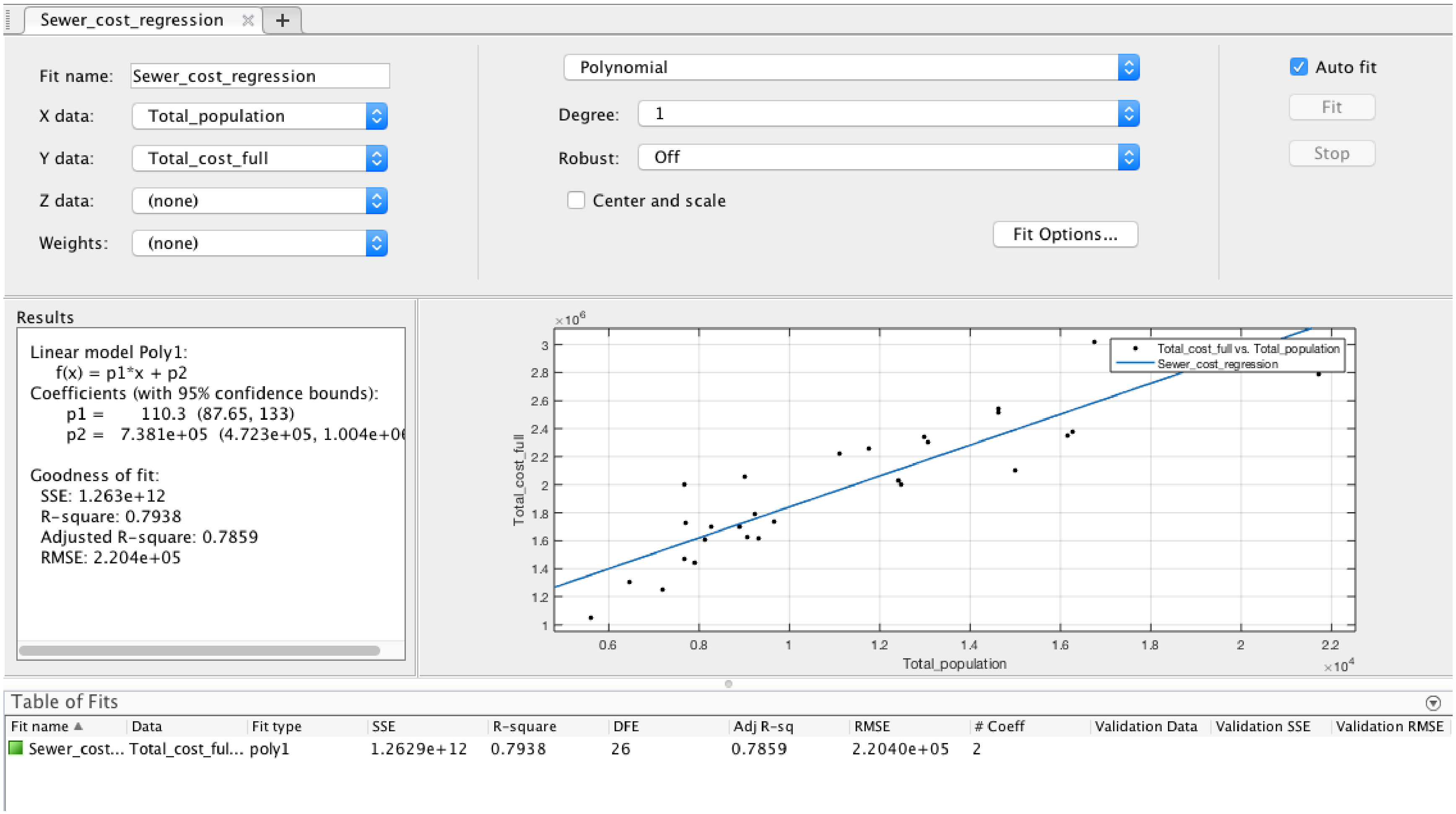


Figure A-1: Linear regression of sewer network cost and total population served.

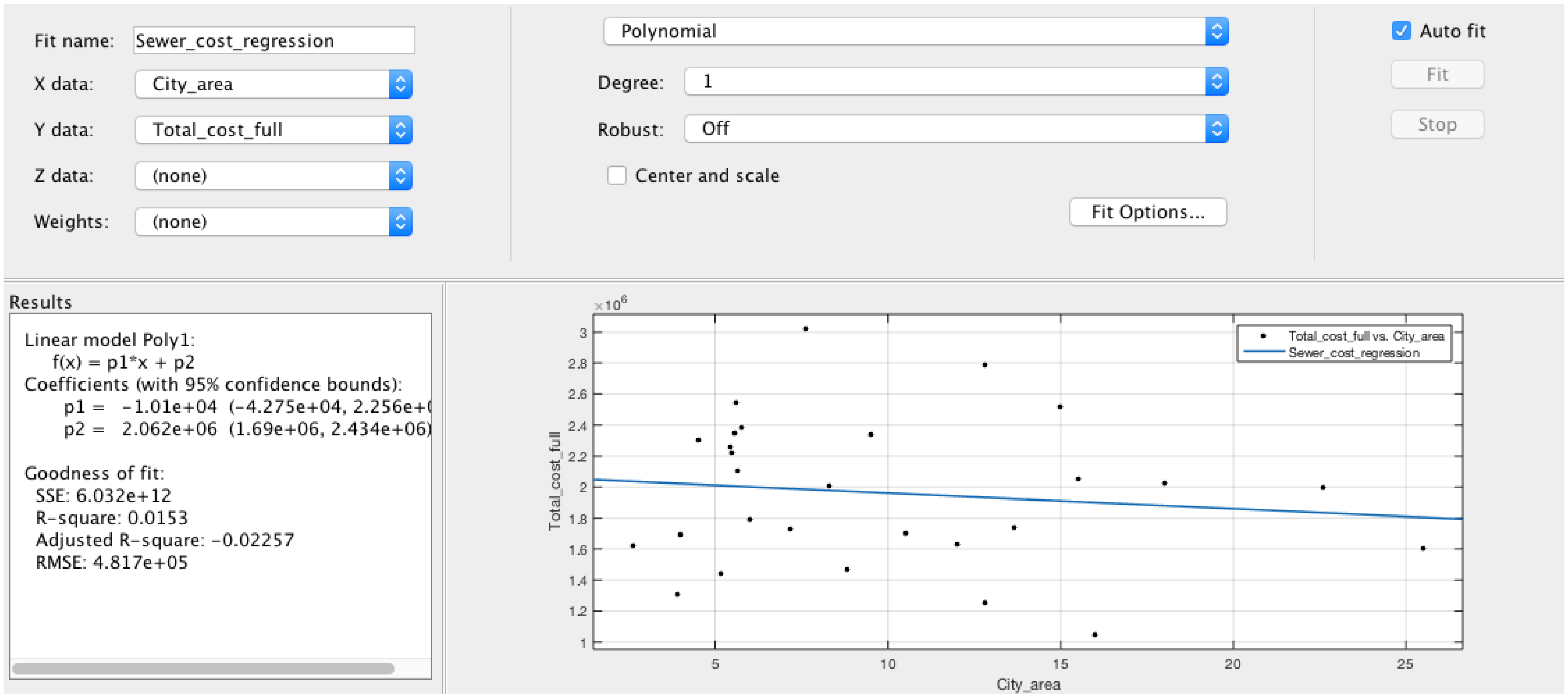


Figure A-2: Linear regression of sewer network cost and land area served. There is no significant correlation. Therefore, this variable was removed from our technoeconomic model.

Table A.2: Table of STP data from Pannirselvam *et al.* 2015. All STPs are based on the Activated Sludge Process. One very high-capacity STP and two large capacity STPs were excluded from the data set due to being outliers. There are factors that affect the cost of an STP other than capacity. In lieu of not having data on those other factors, the specific numbers here are limited to the STPs of Tamil Nadu from this single dataset.

Capacity of STP (MLD)	Year of Installation	Capacity class	Cost of STP (INR 10^6)	Unit cost of STP (INR 10^6 / MLD)	CCI Adjustment factor	Adjusted to 2019 costs	Unit cost of STP (USD 10^6 / MLD)	Unit cost of STP (USD / person)	
2.2	2009	Small	31.59	14.36	1.29	18.5	0.308	33.28	Assume one person = 108 L/day (135 * 0.8L/day)
2.24	2009	Small	32.64	14.57	1.29	18.8	0.313	33.77	
2.96	2009	Small	40.40	13.65	1.29	17.6	0.293	31.63	
3.5	2009	Small	42.10	12.03	1.29	15.5	0.258	27.88	
3.9	2010	Small	47.31	12.13	1.22	14.8	0.247	26.67	
3.99	2009	Small	48.71	12.21	1.29	15.7	0.262	28.29	
4.2	2010	Small	41.40	9.86	1.22	12.0	0.201	21.67	
4.84	2012	Small	49.00	10.12	1.12	11.4	0.190	20.50	
4.86	2010	Small	43.94	9.04	1.22	11.0	0.184	19.88	
6.92	2010	Medium	68.20	9.86	1.22	12.0	0.201	21.67	
7	2009	Medium	66.82	9.55	1.29	12.3	0.205	22.12	
7.38	2008	Medium	70.01	9.49	1.31	12.5	0.208	22.43	
7.65	2010	Medium	73.30	9.58	1.22	11.7	0.195	21.07	
8.7	2009	Medium	79.69	9.16	1.29	11.8	0.197	21.23	
9.63	2009	Medium	86.71	9.00	1.29	11.6	0.193	20.87	
9	2009	Medium	81.05	9.01	1.29	11.6	0.193	20.87	
9	2009	Medium	82.00	9.11	1.29	11.7	0.196	21.12	
10.62	2008	Medium	92.10	8.67	1.31	11.4	0.190	20.50	
12.05	2010	Medium	103.88	8.62	1.22	10.5	0.176	18.96	
12.25	2009	Medium	102.00	8.33	1.29	10.7	0.179	19.30	
13.07	2007	Medium	103.40	7.91	1.43	11.3	0.188	20.35	
23.65	2009	Medium	171.72	7.26	1.29	9.3	0.156	16.83	
23.85	2009	Medium	179.90	7.54	1.29	9.7	0.162	17.48	
40	2007	Medium	194.79	4.87	1.43	7.0	0.116	12.53	
40	2007	Medium	208.30	5.21	1.43	7.4	0.124	13.39	
54	2007	Large	501.06	9.28	1.43	13.3	0.221	23.87	
54	2007	Large	500.55	9.27	1.43	13.2	0.221	23.84	
60	2007	Large	548.37	9.14	1.43	13.1	0.218	23.51	
60	2008	Large	562.06	9.37	1.31	12.3	0.205	22.15	
110	2007	Large	785.16	7.14	1.43	10.2	0.170	18.36	
401.25	2019	Large*	5980.00	14.90	1.00	14.9	0.248	26.83	
							Top quartile	**33.77**	
							3rd quartile	**23.86**	
								Used for requirement	

STP data from Pannirselvam 2015
Based on the Activated Sludge process
1USD = 60INR for this time period
CIDC construction cost index for urban infrastructure cost adjustments with base year 2007
*data from https://economictimes.indiatimes.com/news/politics-and-nation/indias-largest-sewage-treatment-plant-to-come-up-at-okhla-djb/articleshow/69565260.cms?from=mdr

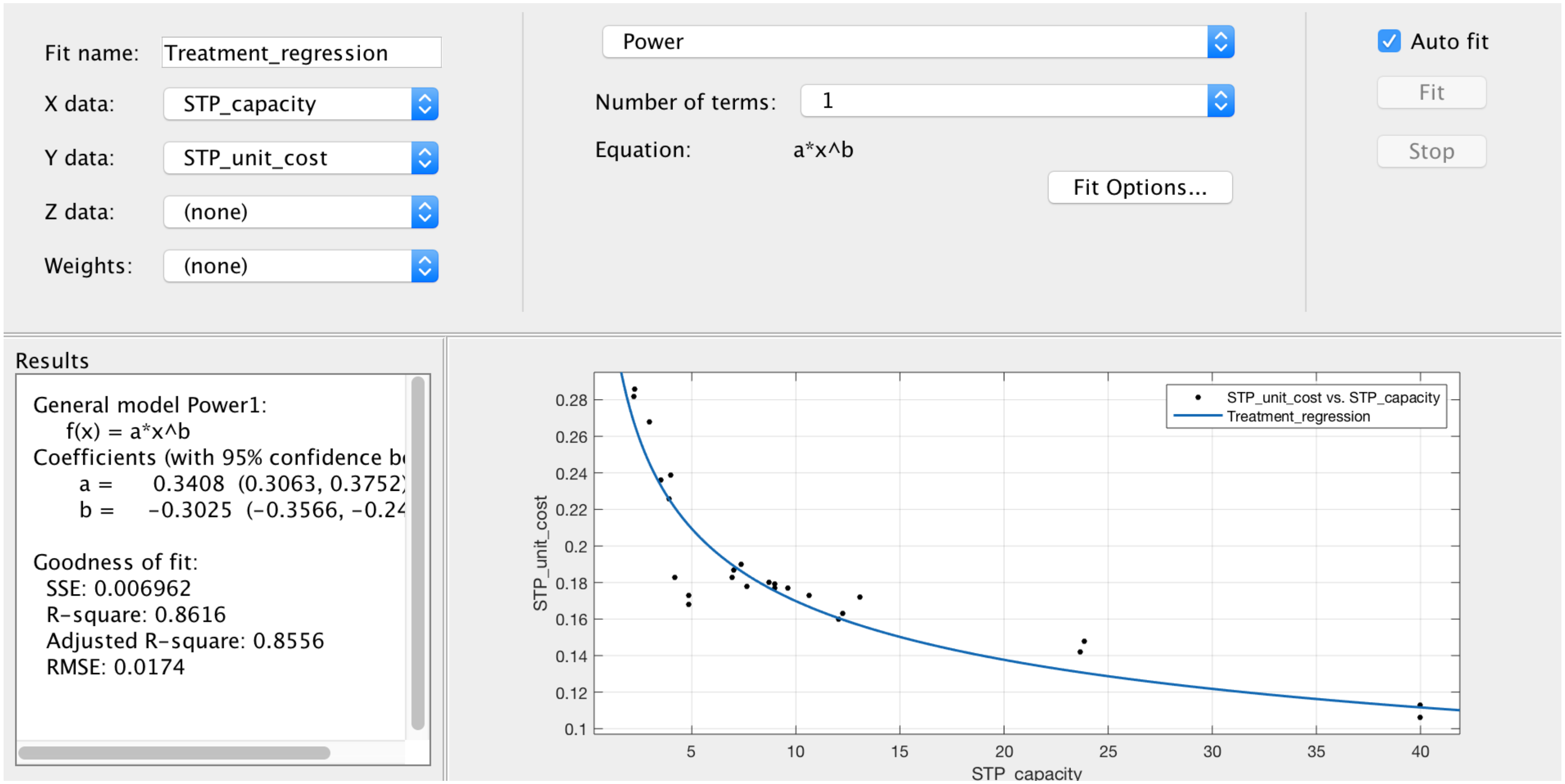


Figure A-3: Regression of the sewage treatment plant unit costs as a function of total plant capacity. This regressed exponential is used in the technoeconomic analysis for sewered systems.

Table A.3: Table of FSTPs from NIUA's 2019 report on "Analysis of Faecal Sludge Treatment Plants in India". The report included eight FSTPs, four of which were liquid and solid treatment, four of which were liquid treatment only. For the liquids-only plants, solids are not fully treated (which also skews the cost of the FSTP downward). For our analysis, we only considered FSTPs capable of full treatment of both liquids and solids.

City	Capacity of FSTP (KLD)	Capacity of FSTP (MLD)	Liquid/Solid Treatment	Capital Cost of FSTP (INR)	Operational Cost of FSTP (INR/year)	Unit capital cost of FSTP (INR/MLD)	Unit operational cost of FSTP (INR/MLD/year)	Unit cost of FSTP (USD/MLD)	Unit operational cost of FSTP (USD/MLD/year)	
Devanahalli	20	0.02	Both	7090000	533000	354500000	26650000	4608500.00	346450.00	0.0751763
Phulera	6	0.006	Both	23945000	708000	3990833333	118000000	51880833.33	1534000.00	0.02956776
Bhuaneshwar	75	0.075	Both	16790000	1206000	223866667	16080000	2910266.67	209040.00	0.07182847
Warangal	15	0.015	Both	11000000	1380000	733333333	92000000	9533333.33	1196000.00	0.12545455
Leh	12	0.012	Liquid Only	5220000	766000	435000000	63833333	5655000.00	829833.33	0.1467433
Jabalpur	50	0.05	Liquid Only	5023000	856000	100460000	17120000	1305980.00	222560.00	0.17041609
Puri	50	0.05	Liquid Only	7390000	1309000	147800000	26180000	1921400.00	340340.00	0.17713126
Tenali	20	0.02	Liquid Only	2000000	553000	100000000	27650000	1300000.00	359450.00	0.2765

Highlighted plants do not meet sustainable sanitaiton goals

Source: National Institute of Urban Affairs 2019 report

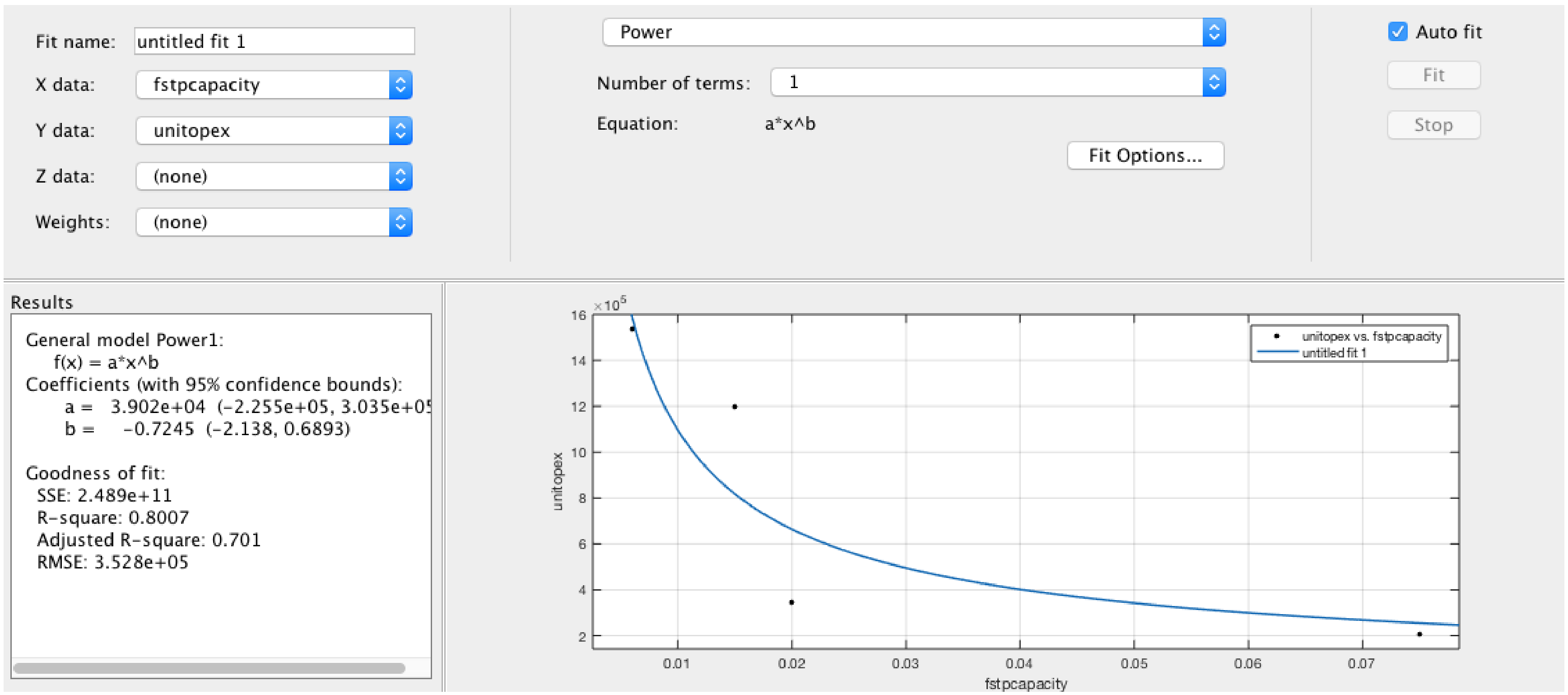


Figure A-4: Regression of the four FSTPs that treat both liquids and solids.

Table A.4: Land costs for the “highest zone" and “lowest zone" correspond with areas close to city center and farther from city center, respectively. Cost data from Chakravorty 2013 are fitted to the exponential model from Bertaud 2015 to yield a “land cost gradient" fitting parameter. Population density data from the GoI 2011 census provides “urban" and “rural" population densities for a given city. These data are then assumed to be correlated with the high and low zones from Chakravorty 2013’s analysis. These two points of reference form the basis for regressing the exponential functions described by Bertaud 2015 with fitting parameter “population density gradient". Some cities are removed because of lack of “rural" data in the census.

Location	Lowest Zone: Cost per sqft (including residential construction)	Highest Zone: Cost per sqft (including residential construction)	Lowest zone: Land cost per sqft (INR)	Highest zone: Land cost per sqft (INR)	Lowest zone: Cost per sqm (INR)	Highest zone: Cost per sqm (INR)	Land cost gradient	Area to urban outskirts (sqkm)	Population density outside urban limits (people/sqkm)	Population density of Highest Zone (people/sqkm)	Population density gradient	
Mumbai	2576	39702	1576	38702	16964	416598	0.269	446.00	19,652	19,652	0.000	Lack of outskirt data
Bangalore	5671	10140	4671	9140	50280	98385	0.042	804.85	627	10,872	0.178	
Delhi	3709	12289	2709	11289	29160	121518	0.074	1156.56	1,284	14,153	0.125	
Chennai	2591	4744	1591	3744	17126	40301	0.115	175.00	0	26,553	#NUM!	Lack of outskirt data
Kochi	2249	7262	1249	6262	13445	67406	0.300	91.02	3,051	4,298	0.064	
Pune	2981	3254	1981	2254	21324	24263	0.008	816.20	2,991	11,848	0.085	
Hyderbad	2312	3435	1312	2435	14123	26211	0.074	217.00	0	18,172	#NUM!	Lack of outskirt data
Faridabad	2081	4007	1081	3007	11636	32368	0.123	218.42	1,169	6,706	0.210	
Kolkata	1747	4235	747	3235	8041	34822	0.191	185.00	0	24,306	#NUM!	Lack of outskirt data
Ahmedabad (Ahmadabad)	1235	2851	235	1851	2530	19925	0.121	920.44	160	6,587	0.217	
Jaipur	1215	3904	215	2904	2314	31259	0.303	232.22	371	9,345	0.375	
Patna	2016	2715	1016	1715	10936	18461	0.056	269.77	1,134	9,321	0.227	
Bhopal	1534	5964	534	4964	5748	53434	0.211	350.05	187	5,477	0.320	
Lucknow	1641	2407	641	1407	6900	15145	0.064	470.71	754	6,456	0.175	
Surat	1661	2411	661	1411	7115	15188	0.060	508.61	305	9,534	0.271	
Average (INR, 2010)	**2348**	**7288**	**1348**	**6288**	**14510**	**67686**						
Average (INR, 2019)	**3544**	**11001**	**2035**	**9492**	**21902**	**102170**						
Average (USD)	**$46**	**$143**	**$26**	**$123**	**$285**	**$1,328**						

Cost of construciton included in figures is about 1000Rs/sqft; this cost is removed to calculate 'Land Cost'

Costs converted from 2010 prices to 2019 using GDP deflator (World Bank, 2016)

"Lowest Zone" prices used assuming that STP and FSTPs would be built in less desirable locations

Costs from Chakravorty 2013

World Bank deflator https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS?end=2019&locations=IN&start=2010

Highest and lowest zone estimates from 2011 Census data Table A-1

Land cost calculation based on RTI cost framework tool

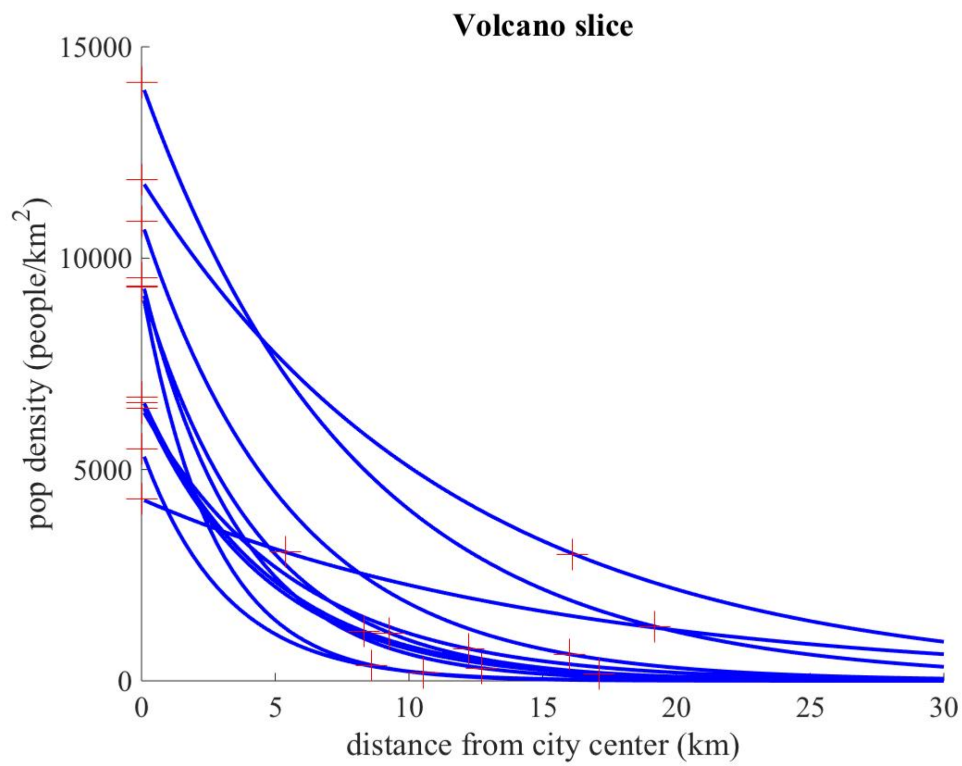


Figure A-5: A radial slice of the “volcano" shapes shown in 2-2. Each blue line is a different city. Red crosses represent the “rural" and “urban" population points of each city.

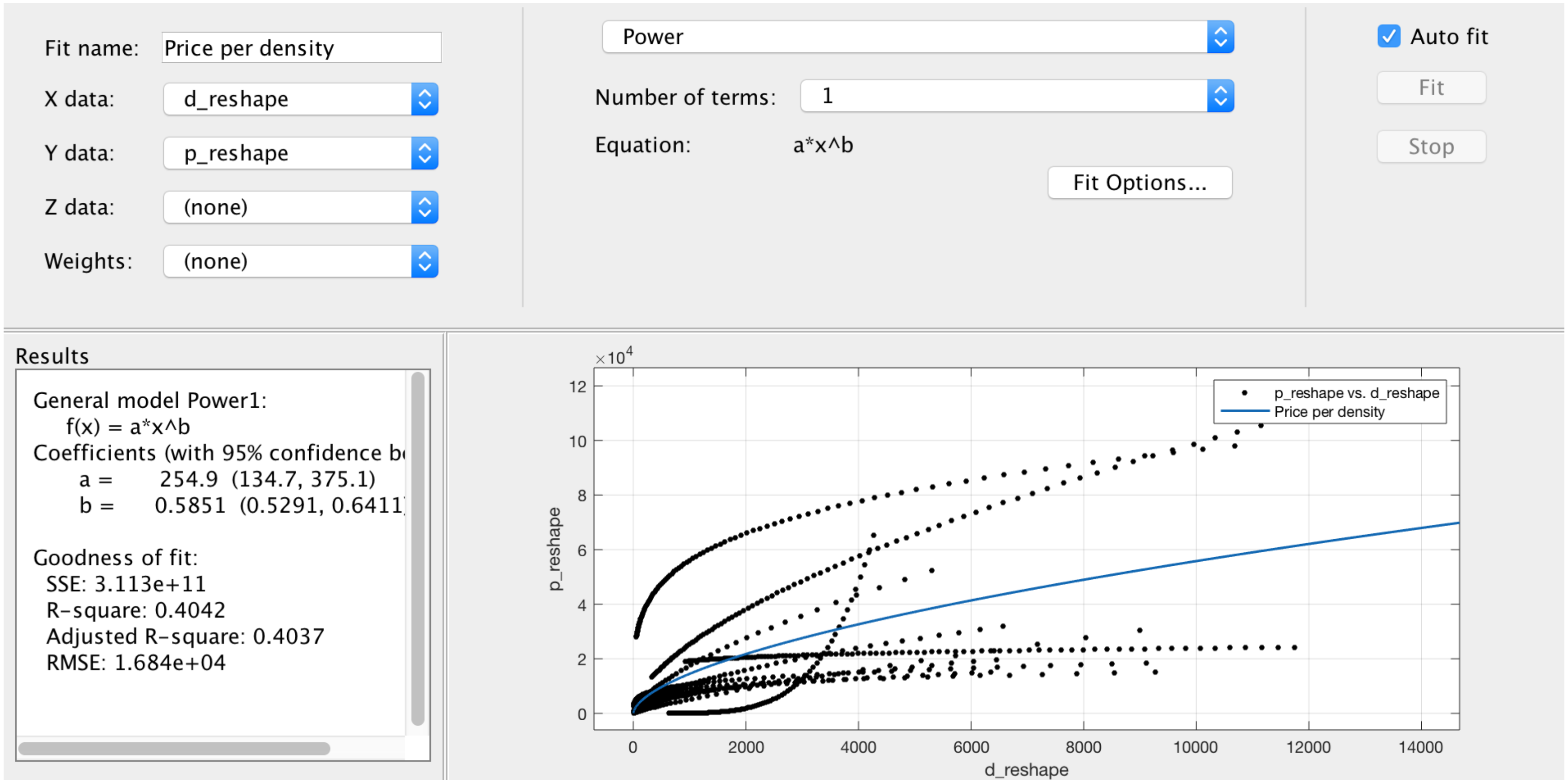


Figure A-6: Land cost regression as a function of population density ($p_reshape$ corresponds to land cost, $d_reshape$ corresponds to population density). Each black dotted curve is a city. Some cities have overall higher prices (more desirable or higher-paying cities) while others are cheaper. One outlier that curves up has a very flat population density gradient (evenly-distributed population) but still has a steep land cost gradient (people still value land highly near the city center). the blue line represents the "average case" line that was used in the technoeconomic analysis' land costs.

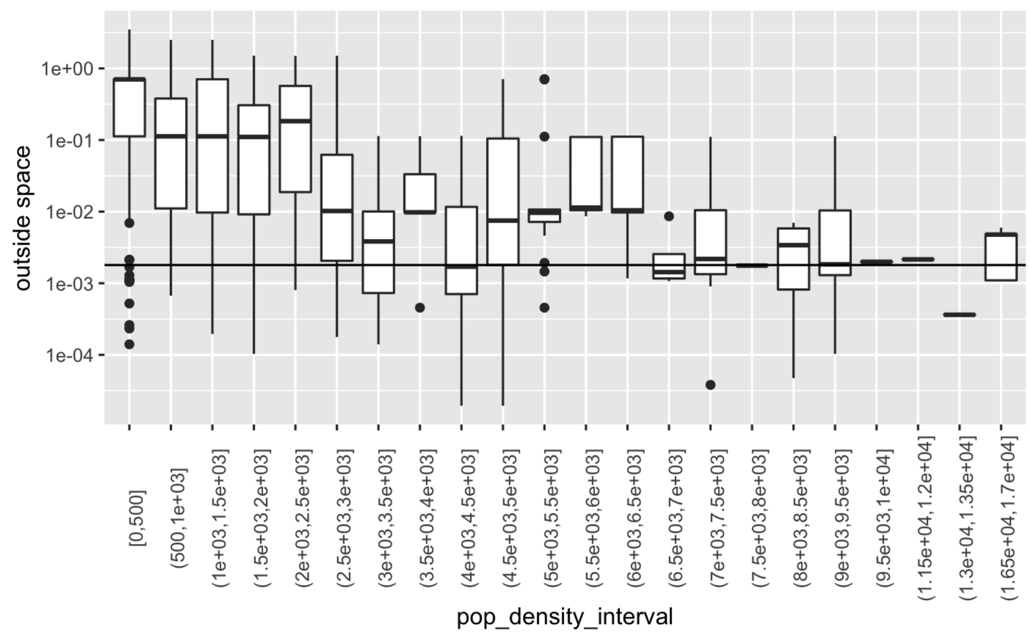


Figure A-7: Data from the National Sample Survey 69$^{\text{th}}$ round split into population density bins 500 wide. Available non-dwelling land (log 10) is plotted on the y-axis. The horizontal black line is the amount of land required for a pit latrine. For each bin, the median person in that population density is marked with a black line, top and bottom quartiles are marked with the whisker, and middle quartiles are marked with the box. Outliers are shown as black dots. Above about 9,500 people per sqkm, the sample sizes get smaller, as these densities are less common. Above about 10,000 people per sqkm, the downward trend of available land crosses over the amount of land required for a pit latrine.

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