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Economic cost analysis of low-cost sanitation technology options in informal settlement areas (case study: Soweto, Johannesburg)

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ABSTRACT

In Urban Africa, water and sanitation utility companies are facing a huge backlog of sanitation provision in the informal settlement areas. In order to clear this backlog, new investment is required. However, to select appropriate sanitation technologies, lifecycle costs need to be assessed. The aim of this research was to establish lifecycle costs for appropriate sanitation technologies in informal settlement areas. Three sanitation options were compared: simplified sewerage, urine diversion dry toilet (UDDT) and Ventilated Improved Pit (VIP) latrine. Three scenarios for simplified sewerage were considered; gravity flow into existing conventional sewers with treatment; new-build with pumping and treatment; and new-build gravity flow with treatment. The study revealed that simplified sewerage is the cheapest option for Soweto informal settlement, even when the costs of pumping and treatment are included. Gravity simplified sewerage with treatment is cheaper than the UDDT system and VIP latrine at all population densities above 158 and 172 persons/ha, respectively. The total annual cost per household of simplified sewerage and treatment was US$142 compared to US$156 and US$144 for UDDT and VIP latrine respectively. The costs of simplified sewerage could be recovered through a monthly household surcharge and cross-subsidy summing US$5.3 The study concluded that simplified sewerage system was the first choice for Soweto informal settlement areas, given the current population density.

1. Introduction

In urban Africa, delivery of sustainable sanitation services in low income and informal settlements is a growing challenge. This is due to rapid increase in the size of the urban population and rising poverty levels coupled with weak or non-existent capacity to deliver basic municipal services at the local level. Few municipal authorities and sanitation utility companies in urban Africa have the capacity to match increasing demand for sanitation services. Consequently, levels of access to sanitation are low. Sub-Saharan Africa as a whole achieved a modest 6% increase in access to sanitation between 1990 and 2015. Overall access remains low at 30% and although access is higher in urban areas, there remain 695 million people in Sub-Saharan Africa who do not have access to a household toilet (UNICEF and WHO, 2015). However, it is important to note that generally, South Africa is in a better sanitation situation than the majority of Sub-Saharan Africa, with reported access to improved sanitation at 66% overall (70% urban, 61% rural). But, this still represents a huge number of households without access to sanitation. Municipal authorities and sanitation utility companies are increasingly experiencing sanitation backlogs, especially in the informal settlements despite their valuable efforts towards addressing the sanitation challenge. For instance, in 2009, there was a sanitation backlog of approximately 30,016 households in the Soweto area of Johannesburg; Johannesburg Metropolitan Municipality (CoJMM) made a commitment to achieve 95% basic sanitation coverage by 2011 but this remained an enormous challenge (Thela, 2007; Official Website of the City of Johannesburg, 2015). Without a step change in the rate of delivery of sustainable and appropriate sanitation, this situation will persist for decades.

A major constraint to effective service delivery is the inability of local authorities to sustain services over time. This is in part because the operational costs of urban sanitation are high, and sustained services usually require a combination of reliable cost-recovery from households and smart delivery of public subsidies (Evans et al., 2009; Manga,

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2017). At a more basic level, there is limited understanding of the real costs of operating both piped (networked sewers) and road-based (on-site) sanitation systems in urban areas. These costs are higher than in rural areas because of lack of space and high population densities means that facilities need to be emptied regularly and faecal sludge transferred to a central point for processing.

Where local authorities are committed to extending services to informal settlements, they may still lack information on the real operational costs of the various viable options. To address this gap we set out to examine the full costs of constructing and operating two promising sanitation technologies, which have been considered by the Government of South Africa for use in urban areas. Our approach uses feasibility-level design to identify the full costs of networked sewers and onsite sanitation options (urine-diverting dry toilets and VIP latrines) in a typical large informal area in Soweto, Johannesburg. We considered capital costs plus operational and maintenance liabilities over a notional ‘lifecycle’ for each system. We used a novel measure, the Total Annual Cost per Household (TACH) to compare full economic costs of each option. The study enabled a review of the key factors which drive full costs of urban sanitation systems and in particular allows for an assessment of the ‘break point’ of population density at which networked piped systems become more cost-efficient when compared to onsite systems.

1.1. Sanitation overview in Soweto

Soweto is an urban region covering approximately 150 km^2, located 16 km southwest of the Johannesburg city, in Gauteng, in the Northeast of the Republic of South Africa. It is mostly populated by black Africans (Tatam, 2010; Harrison and Harrison, 2014).

Most of the population of Soweto lives in informal settlements with lack of access to improved sanitation, and Soweto makes up about 15% of informal settlements in the City of Johannesburg (CoJ). Soweto is the third highest contributor to the population increase of the CoJ and comprises about 43% of the total population of the city. It is estimated that the population density of Soweto is 14 times greater than the national average (Greater Johannesburg Metropolitan Council., 1999; Harrison and Harrison, 2014). Currently, the population of Soweto is estimated at 1.57,864 million people (Population of 2019, 2019), with a population density of 105 persons/ha. (considering its area of 150 km^2). However, some areas in Soweto such as Chiawelo Ext 1, Freedom Charter Square, Mandela view, Winnie Camp, and Meadowlands West Zone 8 have extremely high population densities of approximately 347, 313, 290, 254, and 210 persons/hectare respectively (See Table S3 for other areas) (Frith, 2011).

Provision of sanitation services in Soweto is mainly dependent on the government through the CoJMM (Tatam, 2010; Official Website of the city of Johannesburg, 2010). CoJ has a rapid population growth and increase in household formation especially in the informal settlements of Soweto. This rapid rate of household formation leads to increased demand for sanitation services and reduced space for onsite systems such as pit latrines. This limits the ability of the government to deliver the standard package of a Ventilated Improved Pit (VIP) for each household. This is considered as Level of Service 1 (LOS1) (Official Website of the city of Johannesburg, 2010; Greater Johannesburg Metropolitan Council., 1999; Thela, 2007).

Since the Post-Apartheid government prioritised the provision of basic services such as sanitation to informal settlements that were historically disadvantaged by the apartheid regime, the CoJMM through Johannesburg Water (Pty) Ltd has been making strategies to provide and improve the sanitation services in such areas (Beall et al., 2000a). However, tensions remain between the provision of new improved sanitation services and operation and maintenance of the existing sanitation facilities. Where operation and maintenance funding and capacity is insufficient systems often fail in the medium to long term.

1.2. Sanitation technologies selection criterion

The selection of the most appropriate sanitation technology for informal settlement areas is driven by ground conditions, groundwater characteristics, climatic factors, regulations (including environmental protection, public health, and building codes), and the ability of the local contractors to implement the technology (Kunene, date unknown). To date, the City of Johannesburg has utilized primarily conventional sewerage and Ventilated Improved Pit latrines (VIP). VIP latrines have been provided by the Government of South Africa to households in informal settlements as level of service 1 (LOS1), and their installation cost is about $399 - $448 (excluding the cost of land) (Still et al., 2009). Some small-scale trials of alternative onsite sanitation technology options such as Urine Diversion Dry Toilets (UDDT) have been rolled out since the authorities are interested in the basic dry onsite sanitation services with low risk of ground water pollution. For the purposes of this analysis, both onsite sanitation options (UDDT and VIP latrine) were considered. However, conventional sewerage was excluded from this analysis since previous studies have already shown that it is far more expensive than the alternative low-cost sanitation sewerage technologies such as simplified sewerage system (Sinnatamby, 1983; Mara, 1996; Chinyama et al., 2012; Eslick and Harrison, 2004). For example, Eslick and Harrison (2004), in their pilot study carried out in eThekwini South Africa reported that, the capital costs of conventional sewerage system are twice those of simplified sewerage system, yet both sewerage systems provide all the benefits and convenience of waterborne sanitation. Even worse, conventional sewerage does not offer a flexible layout and therefore, cannot be easily installed in unplanned areas or informal settlements. Furthermore, there is a widely held view that onsite sanitation systems including emptying and transportation of faecal sludge are invariably cheaper than sewerage systems. For example, Dodane et al. (2012) report an analysis from Dakar indicating that the combined capital and operating costs of sewers systems are five times the equivalent costs of onsite sanitation system (including emptying and transportation of faecal sludge). However, this study looked at conventional sewerage systems including very expensive treatment options, while requiring less costly treatment systems for the onsite sanitation system. To-date, there have been a few studies comparing the like-to-like costs of low-cost simplified sewerage with those of onsite sanitation systems. Therefore, to make the best contribution to CoJMM decision making and planning for sanitation service delivery in Soweto, the study examined the relative costs of simplified sewerage and onsite sanitation options (UDDT and VIP latrine).

2. Methodology

2.1. Preliminary survey of literature

The general preliminary survey was conducted through literature review to acquire the basic information required for the design and costing of the two sanitation technologies under consideration. This included both physical and socio–economic data about informal settlement areas in Soweto.

2.2. Pilot sample study area definition and map preparation

The “pilot sample study area” within which research could be carried out was then defined. This was mainly based on settlement and topography characteristics. The selection of the sample study area was based on it being representative of the general conditions in the informal settlement and population in Soweto. A physical survey was also done, to identify locations of different features within the study area that would be vital in the design and costing of the system. The map of the sample study area was then developed showing the existing physical features, infrastructures as well as the hydrogeology of the sample study area as recommended by Sinnatamby (1983).

2.3. Social and physical preliminary survey for the pilot sample study area

The proposed sample area was Chris Hanis informal settlement with a population of 2,000 households. The average size of households within Chris Hanis informal settlement area and Soweto at large is about 3–7 people (Greater Johannesburg Metropolitan Council., 1999), although studies by Mears (2011) and (Loots, 2008) reported an average household size of about 4.8 and 4.2 persons per household in Soweto, respectively. For the purpose of this study, the highest household size of Five (5) persons was considered and therefore, used in the design. The area has a reliable water supply provided by Johannesburg water, although almost all households use a communal standpipe.

For the purposes of detailed design of sanitation solutions, an area covering about 12.9 ha and housing 517 households was selected. This represents a single 'drainage basin' or sub-unit of any proposed sewer network and is thus a useful unit of analysis for comparison of costs of sanitation systems. The current design population is 2,585 persons, and population density is 200 persons/hectare. With the population growth rate of 3% (Population of 2019, 2019), the population size of the studied area was anticipated to be 5255 people at the end of the design period of 25 years, resulting in a population density of 407 persons/hectare and a total of 1,051 households.

Furthermore, Chris Hanis informal settlement area was characterised by; unplanned and irregular distribution of the households (buildings), non-aligned narrow murram roads, moderately flat topography with elevations between 1586 and 1572 m. The survey also showed that there existed conventional sewerage trunk sewers of pipe sizes 600 mm and 2000 mm diameter crossing through the studied area, heading to Bushkoppies wastewater treatment plant. According to Johannesburg Water (2017), Bushkoppie treatment plant has the capacity to handle additional sewerage from our study area, and recently its capacity has been increased to collect and treat all sewage from Soweto East, southern suburbs of Johannesburg, and from the industries to the south of Johannesburg.

2.4. Design of simplified sewerage system

Simplified sewerage is a low-cost off-site sanitation technology designed mainly for collecting, and conveying all forms of unsettled wastewaters from household environment. It is basically a conventional sewerage system stripped down to its hydraulic design basics, so as to allow for the use of smaller-diameter pipes, shallower depths, flatter gradients and reduced manholes while maintaining sound physical design principles (Tilley et al., 2014; Mara, 1996; Sinnatamby, 1983; Türker, 2011). Simplified sewerage layout is very flexible in that it can be implemented in unplanned areas with less destruction and restoration costs since it uses both back yard and in-street layout versions in private land, unlike conventional sewerage where in most cases sewers are laid in the centre of the roads. The system also allows in some cases for community participation in the implementation, operation and maintenance of the system. All such system characteristics and modifications to the design features lead to reduced capital costs of the system, which enables the sanitation service providers to achieve a greater coverage of sanitation services to its citizens with the existing or available financial resources (Paterson et al., 2007). However, it's important to note that although many studies report community participation as one of the key features associated with successful simplified sewerage system, in practice is not really the case as some communities do not actually enjoy participating in sanitation say performing simple operation and maintenance tasks such as unblocking sewers (Tilley et al., 2014). Therefore, in such situations, operation and maintenance works of the system may be delegated to small engineering companies or specialised group of persons trained in appropriate operation and maintenance procedures so as to identify problems early enough prior to them becoming severe hence reducing on the costly repairs (Sinnatamby et al., 1986; Tilley et al., 2014).

2.5. Modelled simplified sewerage system scenarios

The simplified sewerage system was designed following the procedure suggested by Bakalian et al. (1994) and Mara et al. (2001) for a design period of 25 years. An average water consumption of 100 L/person/day was considered during the design since the system does not require much water for its effective operation. Three scenarios of the simplified sewerage systems were considered:

(i) Simplified sewerage discharging collected wastewater into the existing conventional trunk sewers within the study area (assuming a gravity sewer system) with treatment plant.
(ii) Complete (stand-alone) simplified sewerage with treatment plant and pumping station. Assuming the in-block sewer network and treatment plant are in different basins where the flow of the collected wastewater by gravity is not possible, and a pumping station is needed to get the sewage to the treatment plant.
(iii) Complete (stand-alone) simplified sewerage with treatment, but excluding pumping station (assuming a gravity sewer system).

After the design of the system, detailed construction CAD drawings were prepared (See Fig. S4). These formed the basis for estimating quantities and hence construction or capital costs. The drawing list was similar to that recommended by Sinnatamby et al. (1986).

2.6. Shadow factors

The four shadow factors used when determining the economic costs were also obtained after conducting the cost survey, and these included the following:

1) Shadow factor of all labour (skilled and unskilled) was found to be 1, since the sum of minimum wages, benefits, and holiday pays were not different from the actual labour in the construction market.
2) The opportunity cost of capital was found to be 11% (Kuo et al., 2003).
3) The foreign exchange shadow factor was also found to be 1, and the used foreign exchange rate as of 2018 March was 1ZAR = 0.0844 US$.
4) The shadow price of land was also found to be 1, and according to Mail & Guardian. (2019), the cost of the land in Soweto ranges between US$560.5 to 1531.8 per m^2, with an average cost of US $1,028 per m^2.
5) Lastly, the shadow price for water and other resources was not considered so important in this study since the studied project did not involve the purchase of such resources (apart from the AIC of water).

2.7. Full costs of simplified sewerage

The full costs of simplified sewerage system were computed following the procedure suggested by Mara (1996) and Kalbermatten et al. (1982) for economic analysis of sanitation technologies. The cost elements which were taken into account included: capital costs for construction of new infrastructure; operational costs for running the system and maintenance requirements for over the design period of 25 years (see Table S2).

Capital costs were estimated on the basis of a Bill of Quantities prepared from the construction drawings and making use of appropriate specifications (Siglé et al., 2015; Royal Institute of Chartered Surveyors., 1998). Unit rates for items of works and labour were acquired by examining the costs of materials available in the market in Soweto as well as by consultation with local consultancy firms, material and equipment suppliers and review of secondary reports. The estimated costs included costs associated with planning, design, and supervision, construction of household connections (including costs of the toilet structure, and all associated plumbing fittings such as toilet bowl, pipes etc.), land, block and street sewer works, inspection chambers, and pumping stations where necessary.

Operational costs included the costs of operating pumping stations (e.g. fuel and labour) and the costs of operating the sewer network. The cost of operating the network is low since excreta flows through the system of pipes. However, there is a cost associated with the marginal additional water required for flushing toilets to ensure effective operation, when compared to the predominant VIPs in the area. While this is low compared to that required for conventional sewerage, it is still higher than the requirements for most onsite sanitation systems. It was assumed that an additional 10 L/person/day would be required due to the use of the system, mainly for toilet flushing. The estimated additional water quantity used was valued using the cost of production of water at the end of the project lifecycle (AIC of water per m^3). At low levels of consumption, water for domestic use is heavily subsidized in South Africa, however in the estimating of the economic costs, the actual average cost of production of water in Johannesburg was used.

The maintenance costs of the piped network were estimated based on the length of the designed sewer line. Bakalian et al. (1994) found that in Sao Paulo State, it was reported that there were approximately 75 obstructions per 1000 km of sewer each month. Using that as a conservative estimate of blockages, the total blockages likely to occur annually were estimated depending on the total length of the designed sewer. This was then used to estimate the annual cost of hiring sewer rodding machine as well as the annual fuel cost of running the rodding machine while unblocking the sewers. The annual labour cost associated with preventive maintenance works was also estimated. In the system where pumping stations were required, the regular maintenance and pump replacement costs were also considered.

2.8. Full costs of onsite sanitation options (urine diversion dry toilet (UDDT) and VIP latrine)

The UDDT was designed according to the principles suggested by Deegener and Samwel (2015) and Rieck et al. (2012). However, the VIP latrine was designed as a single lined pit with semi-impermeable walls and open bottom following the design principals published by Bester and Austin (1990). Thereafter, detailed construction CAD drawings were prepared, on which the estimates of capital costs of the UDDT and VIP latrine were based for a design period of 12.5 years and 25 years each, respectively. Similar to simplified sewerage system, full costs analysis of UDDT and VIP latrine were conducted following the procedure suggested by Mara (1996) and Kalbermatten et al. (1982). The capital costs of UDDT included construction costs for the super-structure, land, urine diversion pan/toilet, fully-lined vault and soak pit as well as planning, design, and supervision costs. Similarly, the capital costs of VIP latrine included the costs of the super-structure, land, lined-pit with semi-impermeable walls as well as planning, design, and supervision costs.

The operational costs of VIP latrine included costs of emptying, transportation and treatment of faecal sludge at an appropriate treatment location every five (5) year. However, for the UDDT, the operational costs mainly included costs of emptying and transportation of faecal waste for either re-use in agriculture or treatment at an appropriate location every two (2) years, but not the costs of the treatment itself. The treatment costs of UDDT faecal waste are assumed to be negligible since treatment is assumed to take place in the vault of the toilet itself, given the sufficient retention time for thorough pathogen inactivation. The fuel costs incurred during emptying and transportation of faecal waste were not considered separately during the economic costing of UDDT and VIP latrine but instead the fixed costs charged by the desludging operators for emptying the containment system were considered. This is because most of the desludging operators in the developing countries charge a fixed fee from the household for each emptying operation irrespective of the fuel costs, but usually based on the volume of the faecal waste emptied or capacity of the cesspool truck and the distance to the treatment plant or legal disposal location. Lastly, general cleaning and minor maintenance costs especially for repairs of the superstructures (both UDDT and VIP latrine), vault and soak pit (UDDT) as well as lined-pit (VIP latrine) were considered. However, after 12.5 years, another UDDT vault and soak pit was assumed to be constructed since the lifecycle of each UDDT was assumed to be 12.5 years.

2.9. Costs analysis for sanitation technologies studied

For ease of comparison, total annual capital, operation and maintenance costs as well as benefits associated with the use of both sanitation technologies, were converted to a Present Value (PV) (Eqn. 1).

$$\boldsymbol{PV}_t = \frac{FC_t}{(1 + r)^{t-1}} \quad (1)$$

where PV_t = present value of FC_t

FC_t = future benefits or costs incurred in year $\boldsymbol{t}$ and r = the discount rate

The sum of the PV of all total annual costs for all years (t = 1–25) represents the total cost of the project assuming a project period of twenty-five years. This was divided by the PV of the total number of households benefiting from the system to derive the Average Incremental Cost (AIC) per household in each case. This enables the full costs of a range of different systems to be compared (Kalbermatten et al., 1982; Mara, 1996).

Two analyses were carried out. Firstly, a financial analysis, which examined the financial costs of the system including the cost of capital to finance the investment assuming that a loan to finance capital investment and cover the costs of operation is taken out in year 1 and has to be repaid. This allows for the calculation of an optimum annual price per household, which would cover all the associated costs of the system under consideration. However, sanitation has public benefits, and it is widely recognized that public funding for sanitation can be justified particularly in dense urban areas where the health and environmental externalities of good management of excreta may dwarf the private benefits associated with a clean domestic environment. While it is assumed that all the studied sanitation technologies are to provide adequate sanitation for the same number of households, and that the health (and multiple other indirect) benefits could be considered to be the same for all of the scenarios under consideration, it is justifiable to calculate the full economic costs of providing the services. Therefore, an economic analysis was also carried out. In this case, all unit rates used in the generation of the construction, operation and maintenance costs for economic costing were shadow-priced by using the appropriate shadow factors.

2.9.1. Financial costing

This was expressed as the financial costs or monthly surcharge per household. The total financial costs of each of the four options for simplified sewerage were calculated. An annual inflation rate of 0.5% was applied to the cost of fuel to take into account probably, future changes in the relative costs of fuel compared to other inputs. In order to compare a range of scenarios, the present values of all annual expenditures were then calculated using a discount rate of 5.5%. The total number of household served each year was calculated by applying the prevailing population growth rate of 3%. It was assumed that 100% of the required household connections were made in the year of construction and in each of the subsequent years throughout the 25 years design period. However, this may not be the case in real life as the connection usually varies substantially, depending on the social and economic factors. The computed total present value of all the financial costs was divided by the total number of households served, and the number of years of operation of the network to give an indicative financial cost per household per year and per month.

2.9.2. ii) Economic costing

This was expressed as the total annual cost per household (TACH). Shadow pricing was applied to all financial costs to calculate the economic costs. The main difference was found to be the opportunity cost of capital. Returns of up to 11% are possible where capital is invested in more productive sectors. Therefore, a discount rate of 11% was applied to all future costs to calculate total economic costs. The total present value of all economic costs was then divided by the total number of households served annually throughout the entire years of operation of the network to give an indicative economic cost (total annual cost per household). However, in reality, it is hardly the case for the households to pay for all the sanitation costs, as they often receive subsidies from the government to cover whole or part of their sanitation costs. But, the main principle of economic analysis requires that all the costs attributable to a given sanitation option regardless of who incurs them should be considered during economic costing (Mara, 1996). Therefore, all the subsidies provided by the government to individual households on water or/and sanitation were removed, and not considered when conducting economic costing so that the actual cost for use of a given sanitation option can be estimated.

2.9.3. iii) Modelling impacts of population density

To understand the effect of population density on unit costs (TACH), the costing exercise was repeated for notional future scenarios where additional house connections were added to the system. 100persons/hectare increments were adopted and used to compute TACH for the redesigned system in each case. The TACH of the sewerage system was compared with that of onsite sanitation options (UDDT and VIP latrine) at a range of housing densities.

3. Results and discussion

3.1. Cost analysis for simplified sewerage sewer network

3.1.1. Capital costs

The whole sewer network (household connection, block, and street sewer pipes) had a total length of 4237–4732 m, with excavation volume ranging between 1127 and 1902 m^3 depending on the scenario considered. The capital cost of the whole network was found to range between US$ 385,290–452,488 (See Table S1). On average, approximately 4 m of pipework was needed to connect each household to the network. Household connection sewers for the initial 517 household connections required at the start of the design period, accounted for approximately 19–39% of the capital cost, length, and excavation volume of the whole sewer network (See Figure - S3). Lengths and depths of excavation were both low compared to the comparable values for conventional sewer. This could be because the operation of simplified sewerage system requires the collection and convey of all household wastewater from a single housing block by a single small diameter pipeline (in-block sewer) laid at shallow depth and generally flat gradient, which then connects to a nearby trunk sewer by use of a single drop manhole, thus lower capital/construction costs of the system. Unlike, with the conventional sewerage where each of the individual household has its own connection to a trunk sewer, which in most cases is laid around the households in streets.

3.1.2. Operational costs

Depending on the scenario being studied, the total operational costs of the simplified sewerage system varied between US$ 142–89,062(see Table S1). The study revealed that the primary element of the operating costs for the complete simplified sewerage system with pumping station (Scenario 2) was fuel for running the pumping station, as it constituted over 90% of the total lifecycle operational costs of the system. This percentage sometimes might even worsen due to the rapid increase in fuel prices within Soweto and Johannesburg at large. In this study, a sensitivity analysis was conducted to examine the effect of fuel price increase on the operating costs of the simplified sewerage system. The results revealed that an increase in the fuel prices by 1% resulted into 138% increase in the operational costs, and this also resulted into 26% increase in the TACH for the use of the system. This finding suggests that measures should be taken as much as possible when designing the system to eliminate the use of pumping stations as this has proven to be the most expensive unit to operate in the sewerage system. The elimination of pumping stations can be achieved through careful minimisation of the sewer depth as well as avoiding the need for conveying the collected sewage to different drainage basins for treatment or disposal. The total additional quantity of water required per person per year was found to be 3.65 m^3. In Fig. S1, it can be noted that the cost of additional quantity of water required for toilet flushing was negligible. This is because the system requires less quantities of water for its effective operation, resulting into very few quantities of water required for toilet flushing as pour-flush toilets are recommended for use with the system. However, this is different with conventional sewerage system where cistern-flush toilets are usually used because the system requires large quantities of water for its effective operation, all of which results into high costs for flush water required due to the use of the system, hence increase in the operational costs as well as economic cost of the system.

3.1.3. Maintenance costs

The total maintenance costs of the simplified sewerage system ranged between US $ 151,326–156,576 depending on the scenario under consideration (See Table S1). Depending on the scenario designed and studied, labour costs were found to be the primary element of maintenance costs as this constituted approximately 97% of the total maintenance costs of the system. This was because full-time labour is required to do routine maintenance works which may include flushing of sewer lines, removal of blockages, keeping inspection chambers and grease/grit traps free from any substances that could lead to any blockage within the system. Furthermore, unlike in operational costs where the primary element was found to be fuel, in the maintenance cost, the fuel costs for running the sewer rodding machine and hiring costs of the sewer rodding machine were found to be negligible. This is because less blockages are likely to occur in the system since it's usually designed with smaller diameter pipes based on two hydraulic design approaches (i.e. minimum self-cleansing velocity and minimum tractive tension), which both ensure self-cleansing within the sewers (Eslick and Harrison, 2004; Nema, 2009). The use of smaller diameter sewers especially upstream where the flow is low, results in greater depths of flow and higher velocities thus avoiding clogging of sewer pipes (Türker, 2011; Bakalian et al., 1994). In the same vein, previous studies have found properly designed and constructed simplified sewerage systems to usually require very little maintenance works, and thus lower maintenance costs (Sinnatamby et al., 1986; Bakalian et al., 1994; Eslick and Harrison, 2004). Although there is a widely held view that simplified sewerage systems are associated with frequent blockages, experiences from eThekwini show that even with all the shortcomings of the construction and management of the simplified sewerage project, minimal blockages were observed in the system. Only ten (10) blockages were observed during the pilot phase, and these were as a result of poorly sealed pipe ends or poorly closed or unclosed inspection chambers thereby collecting debris and mud from ingress of storm water into the sewer system (Eslick and Harrison, 2004). In addition, Sinnatamby et al., 1986 reported that blockages rarely occur in properly constructed simplified sewer systems in that routine flushing as well as periodic flushing of the sewers lines has been un-necessary for

Table 1
Economic and Financial costs of Simplified Sewerage Systems and On-site Sanitation options (Urine Dry Diversion Toilet and VIP Latrine).

Designed Scenarios[a]	Economic Costing US$ 2018			Financial Costing US$ 2018		
	Total Economic cost	Total Average Cost per Person per Year	Total Average Cost per Household per Year	Total financial cost	Annual cost per household	Monthly cost per Household
System discharging in the existing conventional trunk sewer with treatment (Scenario 1)	598,534	18.6	130.4	626,352	59.1	4.9
Complete system with treatment and pumping station (Scenario 2)	754,651	23.4	164.4	907,684	85.7	7.1
Complete System with pumping station costs excluded (Scenario 3)	651,580	20.3	142.0	679,398	64.1	5.3
Urine Diversion Dry Toilet[c]	755,854[b]	31.3	156.3	-	-	-
Urine Diversion Dry Toilet[d]	688,644[b]	28.5	142.5	-	-	-
Urine Diversion Dry Toilet[e]	803,935[b]	33.3	166.3	-	-	-
VIP Latrine[f]	697,950[b]	28.9	144.4	_	_	_
VIP Latrine[g]	744,997[b]	30.8	154.1	_	_	_
VIP Latrine[h]	571,285[b]	23.6	118.2	_	_	_

[a] Current population density of 200 persons/hectare.
[b] Total Economic cost for installation of 517 on-site sanitation facilities.
[c] UDDT Total Economic cost computed based on the USD$ 931 capital cost of UDDT (cost of land included) determined in this study.
[d] UDDT Total Economic cost computed based on the USD$ 700.1 capital cost of UDDT (cost of land excluded) reported by Rieck et al. (2011). However, when computing the Total Economic cost, the cost of land was considered.
[e] UDDT Total Economic cost computed based on the USD$ 873.6 capital cost of UDDT (cost of land excluded) reported by Mara (2011). However, when computing the Total Economic cost, the cost of land was considered.
[f] VIP latrine Total Economic cost computed based on the USD$ 873.6 capital cost of VIP latrine (cost of land included) determined in this study.
[g] VIP latrine Total Economic cost computed based on the USD$ 783.9 capital cost of UDDT (cost of land excluded) reported by Ulrich et al. (2016). However, the cost of land was included when computing the total economic costs.
[h] VIP latrine Total Economic cost computed based on the USD$ 873.6 capital cost of UDDT (excluding cost of land) reported by Still et al. (2009). However, the cost of land was included when computing the total economic costs.

systems currently in use including those even in the low-water consumption areas.

3.2. Cost analysis for onsite sanitation options (urine diversion dry toilet (UDDT) and VIP latrine)

The construction costs (including the cost of land) of UDDT and VIP latrine per household in Soweto were found to be US$ 931 and US$ 823, respectively (See Table S1). Annual operational and maintenance costs (including costs for emptying and transportation of faecal waste, treatment of VIP sludge, regular maintenance and cleaning) of UDDTs and VIP latrines per household were US$ 29.5 and US$ 56.5, respectively. This results in a total operation and maintenance costs at end of 25 years' period of US$ 185 and US$ 345, respectively (for UDDT), and US$ 445 and US$ 79, respectively (for VIP latrines) (See Table S1). Resulting in a TACH of US$ 156.3 and US$ 144.4 for UDDT and VIP latrines, respectively (assuming again that the opportunity cost of capital is 11%) (See Table 1). This study findings align well with results from Mara (2011) and Rieck et al. (2011) who found that construction costs of UDDT in South Africa were around US$ 873.6 (in 2003, mostly in rural areas) and US$ 700.1 (in eThekwini), resulting in a TACH of US $ 166.3 and US$ 142.5, respectively (See Table 1). In the same vein, the VIP latrine construction costs attained in this study are comparable with those reported by Ulrich et al. (2016) and Still et al. (2009), which were approximately US$ 873.6 (In Uganda) and US$ 783.9 (in eThekwini, South Africa) per household, respectively. These translate to a TACH of about US$ 154.1 and US$ 118.2, respectively (See Table 1). However, it is important to note that capital costs of onsite sanitation facilities (i.e. UDDTs and VIP latrines) and TACH can vary depending on the user budget requirements, preferences, local site conditions, labour costs, material choice and local prices.

This study results show that VIP latrines are 13% cheaper than UDDT to construct in Soweto. Previous researchers have similarly found the construction costs of UDDT to be slightly higher than those of VIP latrines (Von Munch and Mayumbelo, 2007). The higher construction costs associated with UDDT can be attributed to the high costs resulting from the construction of a fully-lined UDDT vault compared to the lined pits with semi-impermeable walls and open bottom of VIP latrines. Further, the operating costs of VIP latrines were slightly higher than those of UDDT, and this this could have been due to the high costs associated with the treatment of VIP faecal sludge (See Table S1). It is important to note that the economic costs and total annual cost per household of the VIP latrine and UDDT at end of 25 years, did not vary substantially as the VIP latrine was only 8% cheaper than the UDDT.

Interestingly, in the present study, the effects of fuel price increase on the operational costs of onsite sanitation options (UDDT and VIP latrine), which included mainly costs of emptying and transportation of faecal waste as well as treatment of VIP sludge, were not noticeable. This may be because in the developing countries most households pay a fixed fee to the desludging operators to empty their containment systems regardless of the changes in the fuel prices. The emptying fees are usually determined based on the volume of the faecal waste emptied or capacity of the cesspool truck, and the distance to the treatment plant or legal disposal point. This study VIP latrines and UDDTs TACH results were considered, and used for comparison purposes with those of simplified sewerage system.

3.3. Economic and financial cost analysis for simplified sewerage system

Table 1 presents a summary of the economic and financial costs of the studied sanitation systems based on the current population density. It can be noted that these costs varied substantially depending the scenario being studied. The results indicate that the total economic costs for construction of 517 onsite sanitation facilities was found to be US$ 755,854 (for UDDT) and US$ 697,970 (for VIP latrine) and those of the modelled simplified sewerage scenarios were in the range of US$ 598,534–754,641 (See Table 1). Given the current population density of 200 persons/hectare, the total average cost per person per year of the simplified sewerage dropped considerably to the range of US$ 18.6–23.5, which was lower than that of the onsite sanitation (UDDT and VIP latrine) in the range of US$ 28.9–31.3. This is because, at high population densities, off-site sanitation systems achieve economies of scale, and this is discussed in detail in the sections below.

It can be noted from Table 1, that the modelled Scenario 1, Scenario 2, and Scenario 3 of the simplified sewerage required a total financial cost of US$ 626,352, US$ 907,684, and US$679,398, and given the 25 years, design period this resulted in a monthly household surcharge of US$4.9, US$7.1 and US$5.3, respectively. Scenario 1 required the lowest financial cost and a monthly household surcharge of US$4.9. This is because the scenario excludes the high costs associated with both the pumping station and main collector sewer as it assumes a gravity sewer system with discharge of the collected sewage into an existing conventional trunk sewers. In situations where pumping was required (Scenario 2), the total financial cost of the sewerage system and monthly household surcharge increased considerably by 45%. This exhibited that the costs associated with the pumping station have a substantial effect on the total cost of the simplified sewerage system as well as monthly surcharge per household. This may be due to the huge operation and maintenance costs associated with the pumping station operation. However, considering a stand-alone gravity sewer system (Scenario 3) with the main sewers (no discharge of the collected sewage into an existing conventional trunk sewers), resulted in only a 8% increase in the monthly household surcharge. This implies that the construction cost of the main sewers to the treatment plant had generally less effect on the total cost of the system as well as the monthly surcharge per household for the use of the sewerage system. Generally, the costs of all modelled scenarios 1–3 with treatment are probably artificially high, because in reality you would have a treatment facility shared between several settlements the size of Chris Hanis, and although, the larger size means higher costs, but there would be economies of scale.

3.4. Population density effect on TACH

This section aims at analysing the effects of population density on the TACH of proposed low-cost sanitation technologies in the studied area. The results presented in Figs. 1 and 2 below, demonstrate that the TACH of the simplified sewerage system decreased as the population density of the area increased. The TACH of the onsite sanitation options (UDDT and VIP latrine) remained constant despite the changes in the population density. The onsite sanitation options (UDDT and VIP latrine) had a uniform total annual cost per household, because the changes in population density of the areas had no effect on the technology's total costs. The installation, operation and maintenance costs remained the same per household. However, this was completely different for the simplified sewerage system as the same installed block, street collector and main sewers of the system were to be used to serve additional population size or households within the area, hence reducing the average construction costs of the system per household. This in turn also led to a reduction in the average incremental cost of the system as well as TACH. More still, the reduction in the average incremental cost and TACH of the sewerage system was also due to the use of the same operation, maintenance and construction costs to cover or serve an additional population or household size. For example, maintenance costs of the sewerage system, which was designed to serve 517 households, could be used to maintain the same sewer, when additional 100 household sizes have connected to it, hence reducing the average incremental cost of the system as discussed above. Furthermore, Figs. 1 and 2 below, illustrates that at a certain population density the simplified sewerage system became cheaper than onsite sanitation options (UDDT and VIP latrine). However, the population densities at which the system became cheaper than onsite sanitation

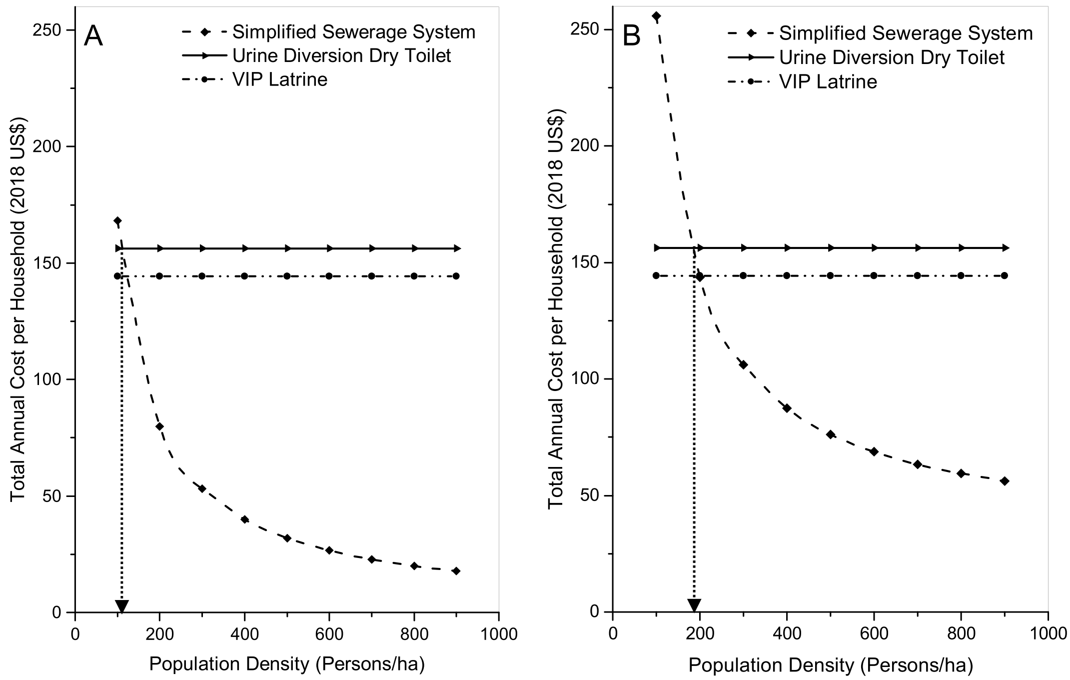

Fig. 1. Population density effects on TACH of Simplified sewerage system and UDDT system in Chris Hanis in comparison with (A) Scenario 1: Simplified Sewerage System discharging in the existing conventional trunk sewer, and (B) Scenario 2: Complete Simplified sewerage system with treatment plant and pumping station.

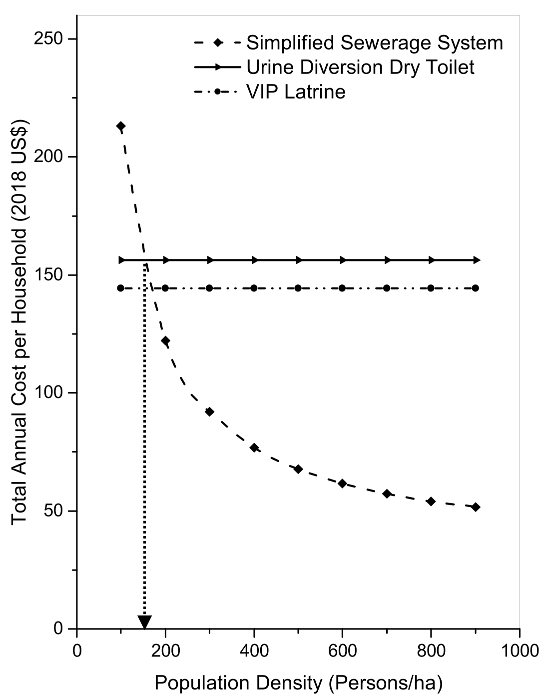

Fig. 2. Population density effects on TACH of Simplified sewerage system and Onsite Sanitation options (UDDT and VIP latrine) in Chris Hanis in comparison with Scenario 3: Complete Simplified Sewerage system with treatment plant but excluding pumping station costs.

options varied depending on the scenario under consideration.

3.4.1. Scenario 1: simplified sewerage system discharging in the existing conventional trunk sewer, with treatment plant

The results of this scenario (Fig. 1 A) demonstrate that TACH of the system reduced from US$168 to US$18 at a population of 100 persons/ha to 900 persons/ha respectively. It further reveals that sewerage system became cheaper than onsite sanitation UDDT and VIP latrine at population densities as low as 112 and 121 persons/ha, respectively. This implies that at the current population density of 200 persons/ha within Chris Hanis, the simplified sewerage is cheaper than onsite sanitation UDDT and VIP latrine.

3.4.2. ii) scenario 2: complete simplified sewerage system with treatment plant and pumping station

Fig. 1 B, presents the results of scenario 2, and it is seen from the figure that TACH of the system reduced from US$256 to US$56 at the population density of 100 persons/ha to 900 persons/ha, respectively. More still, that sewerage system became cheaper than UDDT and VIP latrine at a population density of 188 and 198 persons/ha, respectively. Considering the current population density in the studied area of 200 persons/ha, it is can be confirmed that simplified sewerage is still cheaper than both onsite sanitation options. The increase in the population density at which the sewerage system became cheaper than the onsite sanitation options in this scenario was due to an increase in the total costs of the system, which was because of the added pumping station costs. This, in turn, resulted in an increase in the average incremental cost of the system as well as the TACH.

3.4.3. iii) scenario 3: complete system with treatment plant but excluding pumping station costs

According to the results of this scenario presented in Fig. 2, the TACH of the simplified sewerage system reduced from US$213 to US $52 at the population of 100 persons/ha to 900 persons/ha, respectively. The sewerage system became cheaper than onsite sanitation UDDT and VIP latrine in this scenario at a population density of as low as 158 and 172 persons/ha, respectively. Therefore, based on the current population density within the studied area, which is 200 persons/ha, it is evident that simplified sewerage is still cheaper than onsite sanitation even in this scenario. The decrease in the population density at which the sewerage system became cheaper than the onsite sanitation compared to that in scenario (2) was due to the huge decrease in the total costs of the system, which was because of the excluded pumping station installation and operation costs. This, in turn, resulted in a decrease in the average incremental cost of the system as well as TACH.

This study results suggest that simplified sewerage system is the most viable and economically feasible low-cost sanitation technology for implementation in most peri-urban and informal settlement areas. This is because it has been found to be cheaper than onsite sanitation options at very low population densities (172 persons/ha) than those found in several peri-urban and informal settlement areas in Urban Africa, Asia and Latin America. Therefore, sanitation engineers and planners should consider the installation of this sewerage system as the basic sanitation service in informal settlement areas found in Soweto (such as Chiawelo Ext 1, Freedom Charter Square, Mandela view, Winnie Camp, and Meadowlands West Zone with population densities of 347, 313, 290, 254, and 210 persons/ha. respectively (see Table S3)), Kibera in Kenya (with a population density of 3,000 people/ha), and other parts of Africa, and Asia characterised by high population densities. This will enable relevant government authorities to clear the backlog of sanitation provision in these areas, and thus improving the progress to SDG target 6.2.

3.5. Implication of results

The study revealed that the population density at which simplified sewerage system became cheaper than onsite sanitation (UDDT and VIP latrine) in the Chris Hanis informal settlement area was between 112 and 198 persons/ha depending on the scenario under consideration. These results correlate well with the 160 and 175 persons/ha reported by Sinnatamby (1983) and Nema (2009), respectively, in Natal N.E Brazil. This study and previous studies have confirmed that simplified sewerage is an attractive option from a cost-efficiency perspective at population densities in excess of between 112 and 198 persons/hectare. The relative break-point is dependent on whether or not existing trunk transportation and treatment options are available. However, it is important to bear in mind that this caveat also applies to onsite sanitation systems, from which faecal sludge must be emptied and transported for treatment.

Notwithstanding its inherent cost-efficiencies at high population densities, simplified sewerage remains relatively rare in Sub-Saharan Africa. Various theories have been put forward as to why that is. In part it may be due to the absence of a coherent policy for the provision of fully-managed sanitation in urban areas, and in particular in informal urban areas. Recent work by Peal et al. (2014) noted the absence of a recognition of the need for proper management of faecal sludge in most urban sanitation policies globally, and in the same study observed the propensity for national standards and technical guidelines to focus on conventional sewerage which is impractical and prohibitively expensive in most densely-settled informal areas. Very few urban local governments or water utilities actually calculate the real costs of managing onsite systems which comprise the costs of emptying and transporting wet pathogenic faecal sludge by road to treatment and of operating those treatment plants. Onsite systems are therefore often referred to as ‘low-cost’ but this probably does not reflect the reality if they are to be properly managed. There is also an inherent association between conventional sewerage and ‘modernity’ which may preclude the selection of more appropriate designs in some cases. For example, Beall, Crankshaw and Palnell (2000b) reported that in post-apartheid South Africa, conventional sewerage which is a norm for formal settlements and historically white area, was for some reasons expected by communities to have it extended to the informal settlement areas, despite the high costs associated with it (See Paterson, Mara and Curtis (2007) for details on barriers to implementation of low-cost sewerage systems). These study findings are specific to the Soweto context, but raise the possibility that simplified sewerage may have lower lifetime costs than onsite sanitation systems in other high density low-income and peri-urban contexts. In the same vein, it's important to note that although the economic costs of the studied sanitation technologies may vary depending on the context, the population densities at which the simplified sewerage system becomes cheaper than onsite sanitation systems may not vary significantly, if proper economic costing principles are followed.

4. Conclusions

This study examined the full costs of three ‘low-cost’ alternatives to existing sanitation systems in Soweto, South Africa. The following conclusions were drawn;

1. The total annual cost per household (TACH) of the UDDT and VIP latrine in Chris Hanis was US$156.3 and US$144.4 respectively, this was cost-effective compared to sewerage in population densities less than 158 persons/ha (UDDT) and 172 persons/ha (VIP latrine). However, it also varied between population densities less than 112–198 persons/ha depending on the situation studied. It was confirmed that onsite sanitation options (UDDT and VIP latrine) were uneconomical for use in the informal settlement areas of Soweto where the population densities were more than 172 persons/ha.
2. The average TACH of simplified sewerage system in Soweto was US$ 142, and it varied between US$130.4 to US$164.4 depending on the local condition within the studied area. The system was cheaper than both onsite sanitation options at population densities greater than 172 persons/ha (ranging from 112 to 198 persons/ha. depending on the scenario under consideration). The actual population density in Chris Hanis is much greater than this, hence the system was the most economical for the existing situation. This finding is likely to be true in the majority of informal settlement areas in urban Africa. Johannesburg Water should consider simplified sewerage system as viable and economic technology in the informal settlement areas in Soweto so as to reduce the sanitation backlog in such areas.
3. The financial costs for the use of Simplified sewerage system in Chris Hanis varied between US$4.9 to US$7.1 per household per month depending on whether the system could be connected to existing trunk services and treatment or had to have a stand-alone treatment plant associated with it. The costs of simplified sewerage in this case could be recovered through monthly household surcharge and monthly cross-subsidy summing US$5.3.
4. The population densities below 112 persons/hectare, simplified sewerage was more expensive than both onsite sanitation options regardless of the modelled scenario. However, for population densities above 198 persons/hectare, the sewerage system became cheaper than both onsite sanitation options. This finding suggests that in high density low-income and peri-urban areas which we find all over the developing world, simplified sewerage is most likely to be the sanitation technology of the first choice.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2019.06.012.

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