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. Two sanitation options were compared: simplified sewerage, and urine diversion dry toilet (UDDT). Four scenarios for simplified sewerage were considered; gravity flow into existing conventional sewers; new-build with pumping and treatment; new-build with pumping and excluding 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 at all population densities above 173 persons/ha. The total annual cost per household of simplified sewerage and treatment was US$49 compared to US$113 for UDDT. The costs of simplified sewerage could be recovered through a monthly household surcharge and monthly cross-subsidy summing US$3.0. The study concluded that simplified sewerage system was the first choice for Soweto informal settlement areas, given the current population density.

Keywords: Lifecycle costs; Low-cost sanitation; Simplified sewerage system; Urine Diversion Dry Toilet.

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 achieving 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. 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 an ecological on-site sanitation system (urine-diverting dry toilets) 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 on-site systems.

Sanitation Overview in Soweto

Soweto is an urban region covering approximately 150km^2, located 16km southwest of the Johannesburg city, in Gauteng, in the Northeast of the Republic of South Africa. It is mostly populated by black Africans (Loots, 2008; Tatam, 2010).

Most of the population of Soweto lives in informal settlements with the 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 has a high population density of about 2000 people/km^2, which is 14 times greater than the national average (Greater Johannesburg Metropolitan Council., 1999; Loots, 2008).

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.

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). Some small-scale trials of alternative on-site sanitation technology options such as Urine Diversion Dry Toilets (UDDT) have been rolled out. For the purposes of this analysis, VIPs were excluded on the grounds that their capital and operational costs should already be known to the CoJMM, as they provided them to the households as Level of Service 1 (LOS1). However, it is important to note that the economic costs of on-site sanitation facilities such as VIP latrine and Urine diversion toilet do not vary significantly. Conventional sewerage was also ruled out for the network within the built-up area 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). 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. 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 on-site 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 on-site sanitation system. To-date, there have been a few studies comparing the like-to-like costs of low-cost simplified sewerage with those of on-site 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 UDDT.

METHODOLOGY

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.

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).

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 Loots (2008) reported an average household size of about 4.2 persons per household in Soweto. For the purpose of this study, the highest household size of seven (7) 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 hectares 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 3,619 persons, and population density is 281persons/hectare. With the population growth rate of 4%, the population size of the studied area was anticipated to be 9,277 people at the end of the design period of 25 years, resulting in a population density of 719 persons/hectare and a total of 1,325 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 600mm and 2000mm 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.

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). 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).

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 litres/ person/day was considered during the design since the system does not require much water for its effective operation. Four 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).

(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) Simplified sewerage excluding treatment plant. Assuming the in-block sewer network and the final destination of collected wastewater are in different basins, where the flow of sewage by gravity is not possible, and thus a pumping station is needed to get the sewage to its final destination (e.g. existing conventional trunk sewers).

(iv) Complete (stand-alone) simplified sewerage with treatment plant, but excluding pumping station (assuming a gravity sewer system).

After the design of the system, detailed construction CAD drawings were prepared (See Figure 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).

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) Lastly, the shadow price for land, 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).

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; Barker, 1970). 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, block and street sewer works, inspection chambers, and pumping stations where necessary. The costs of the superstructure and pour-flush toilet bowl were not considered in the present study as it was assumed that households could either modify an existing VIP or construct a simple toilet inside the house, and costs of the pour-flush toilet bowl and urine diversion pan don’t vary significantly.

Operating 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 litres/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 1000km 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.

Full Costs of Urine Diversion Dry Toilet (UDDT)

The UDDT was designed according to the principles suggested by Deegener and Samwel (2015) and Rieck et al. (2012). Thereafter, detailed construction CAD drawings were prepared, on which the estimates of capital costs of the UDDT were based for a design period of 12.5 years each. Similar to simplified sewerage system, full costs analysis of UDDT were conducted following the procedure suggested by Mara (1996) and Kalbermatten et al. (1982). The capital costs included construction costs for the vault and soak pit as well as planning, design, and supervision costs. Similar to the simplified sewerage costing, the costs of the supper-structure and urine diversion pan/ toilet were not considered as it was assumed that households could either modify an existing VIP latrine or construct the UDDT and vault inside the house. The operation costs included mainly costs of emptying and transportation of faecal waste for treatment at an appropriate treatment location every two years, but not the costs of the treatment itself. The treatment costs 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 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 vault and soak pit 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.

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. A).

$$\mathbf{P}V_t = \frac{FC_t}{(1+r)^{t-1}}$$ …………………… Eqn. (A) Where PV_t = present value of FC_t

FC_t = future benefits or costs incurred in year **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.

i) 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 4%. 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 significantly, 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.

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 especially in the developing countries, as they often receive subsides from the government to cover whole or part of their sanitation costs. But, the main principal 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.

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 UDDT at a range of housing densities.

Results and Discussion

Cost Analysis for Simplified Sewerage Sewer Network

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 – 1902 m^3 depending on the scenario considered. The capital cost of the whole network was found to range between US$ 109,294 – 207,483 (See Table S1). On average, approximately 4m 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 20 - 38% 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.

Operation costs: Depending on the scenario being studied, the total operation costs of the simplified sewerage system varied between US$ 205 – 75,780 (see Table S1). The study revealed that the primary element of the operation costs for the complete simplified sewerage system with pumping station (Scenario 2 and Scenario 3) was fuel for running the pumping station, as it constituted over 90% of the total lifecycle operation cost of the system. This percentage sometimes might even worsen due to rapid increase in fuel prices within Soweto and Johannesburg at large. In this study, a sensitive analysis was conducted to examine the effect of fuel price increase on the operation cost of the simplified sewerage system. The results revealed that an increase in the fuel prices by 1% resulted into 138% increase in the operation costs and this also resulted into 25% increase in the TACH for the use of the system. This finding suggest 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/ equipment 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 sewerage to different drainage basins for treatment or disposal. The total additional quantity of water required per person per year was found to be $3.65m^3$. In Figure 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 operation cost as well as economic cost of the system.

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 preventive maintenance, i.e. keeping inspection chambers and grease/grit traps free from any substances that could lead to any blockage within the system. Furthermore, unlike in operation 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 mainly. This is because less blockages are likely to occur in the system. 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). In addition, Sinnatamby 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 systems currently in use including those even in the low-water consumption areas.

Cost Analysis for Urine Diversion Dry Toilet (UDDT)

The construction costs of UDDT per household in Soweto was found to be US$ 590 (See Table S1). Annual operation and maintenance costs (including costs for emptying and transportation of faecal waste, regular maintenance and cleaning) of UDDTs per household were US$ 33.8. This results in a total operation and maintenance costs at end of 25 years' period of US$ 222 and US$ 248, respectively (See Table S1), and a TACH of US$ 113.4 (assuming again that the opportunity cost of capital is 11%) (See Table 1). This finding aligns well with results from Mara (2011) who found that construction costs of UDDT in South Africa were around US$ 873.6 per household in 2003, mostly in rural areas, resulting in a TACH of US$ 152.4. In the same vein, the UDDTs construction costs attained in this study are comparable with those reported seven years back by Rieck et al. (2011) from the pilot projects in Kenya (rural household) and South Africa (eThekwini), which were US$ 609 and US$ 700.1 per household, respectively. These translate to a TACH of about US$ 116.0 – 128.5 (See Table 1). However, it is important to note that capital costs of UDDTs and TACH can vary depending on the user budget requirements, preferences, local site conditions, labour costs, material choice and local prices. Interestingly, in the present study, the effects of fuel price increase on the operation costs of UDDT (which included mainly costs emptying and transportation of faecal waste) 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 UDDTs TACH results were considered and used for comparison purposes with those of simplified sewerage system.

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 significantly depending the scenario being studied. The results indicate that the total economic costs of the on-site sanitation UDDT was US $ 1,060 and this was about 358 times lower than those of the modelled simplified sewerage scenarios, which were in the range of US$ 279,483 – 466,592 (See Table 1). Surprisingly, given the current population density of 281 persons/hectare, the total average cost per person per year of the simplified sewerage dropped significantly to the range of US$ 6.1 – 10.1, which was considerably lower than that of the on-site sanitation UDDT of US$ 16.2. 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.

Table 1: Economic and Financial costs of Simplified Sewerage Systems and Urine Dry Diversion Toilet

Designed Scenarios*	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 (Scenario 1)	279,483	6.1	42.4	307,242	28.1	2.3
Complete system with treatment plant and pumping station (Scenario 2)	466,592	10.1	70.8	619,565	56.6	4.7
Complete system with Treatment plant costs Excluded (Scenario 3)	409,038	8.9	62.1	562,011	51.4	4.3
Complete System with pumping station costs excluded (Scenario 4)	363,521	7.9	55.2	391,280	35.8	3.0
Urine Diversion Dry Toilet[i]	1,060	16.2	113.4	-	-	-
Urine Diversion Dry Toilet[ii]	1,201 -1084	18.4 -16.6	128.5 -116.0	-	-	-
Urine Diversion Dry Toilet[iii]	1,424	21.8	152.4	-	-	-

*Current population density of 281persons/hectare

[i] UDDT Total Economic cost computed based on the USD$ 590 capital cost of UDDT determined in this study.

[ii] UDDT Total Economic cost computed based on the USD$ 609 - 700.1 capital cost of UDDT reported by Rieck et al. (2011).

[iii] UDDT Total Economic cost computed based on the USD$ 873.6 capital cost of UDDT reported by Mara (2011).

It can be noted from Table 1, that the modelled Scenario 1, Scenario 2, Scenario 3 and Scenario 4 of the simplified sewerage required a total financial cost of US$307,242, US$619,565, US$562,011 and US$391,280, and given the 25 years, design period this resulted to a monthly household surcharge of US$2.3, US$4.7, US$4.3 and US$3.0, respectively. Scenario 1 required the lowest financial cost and monthly household surcharge of US$3.8. This is because the scenario excludes the high costs associated with both the treatment plant and pumping station 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 3), the total financial cost of the sewerage system and monthly household surcharge increased considerably by 87%. This exhibited that the costs associated with the pumping station have a significant 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. Surprisingly, adding construction costs of the treatment plant to the gravity sewer system (Scenario 4) resulted in only 30% increase in the monthly household surcharge. This implies that the construction cost of 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. However, the addition of both treatment plant construction costs and pumping costs (Scenario 2), resulted in 104% increase in the monthly household surcharge. This high percentage increase might have been even higher if the operation costs of the treatment plant were included in the total cost of scenario 2. Generally, the costs of the scenarios 2 and 4 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.

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 studied area. The results presented in figure 1 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 UDDT option remained constant despite the changes in the population density. The onsite sanitation UDDT 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, Figure 1 below illustrates that at a certain population density the simplified sewerage system became cheaper than onsite sanitation UDDT. However, the population densities at which the system became cheaper than on-site sanitation varied depending on the scenario under consideration.

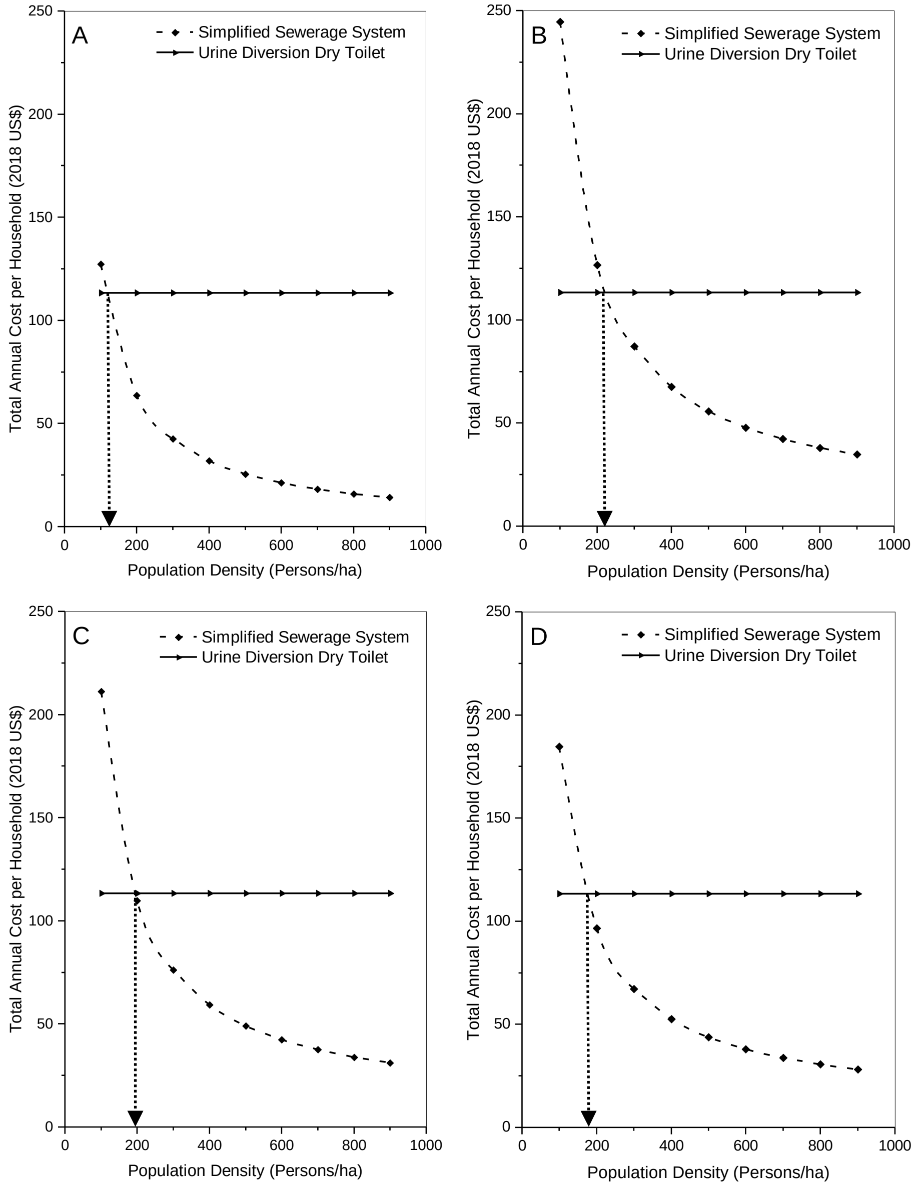

Figure 1: Population density effects on TACH of Simplified sewerage system and UDDT system in Chris Hanis in comparison with (A) Scenario 1: Simplified Sewerage System discharging in the existing conventional trunk sewer, (B) Scenario 2: Complete Simplified sewerage system with treatment plant and pumping station, (C) Scenario 3: Simplified sewerage system with pumping station but excluding treatment plant costs and (D) Scenario 4: Complete Simplified Sewerage system with treatment plant but excluding pumping station costs.

i) Scenario 1: Simplified Sewerage System discharging in the existing conventional trunk sewer

The results of this scenario (Figure 1 A) demonstrate that TACH of the system reduced from US$127 to US$14 at the population of 100 persons/ha to 900 persons/ha respectively. It further reveals that sewerage system became cheaper than onsite sanitation UDDT at population densities as low as 118 persons/ha. This implies that at the current population density of 281 persons/ha within Chris Hanis, the simplified sewerage is cheaper than on-site sanitation UDDT.

ii) Scenario 2: Complete Simplified sewerage system with treatment plant and pumping station

Figure 1 B, presents the results of scenario 2, and it is seen from the figure that TACH of the system reduced from US$245 to US$35 at the population density of 100 persons/ha to 900 persons/ha, respectively. More still, that sewerage system became cheaper than UDDT at a population density of 216 persons/ha. Considering the current population density in the studied area of 281 persons/ha, it is can be confirmed that simplified sewerage is still cheaper that on-site sanitation UDDT. The increase in the population density at which the sewerage system became cheaper than the on-site sanitation was due to an increase in the total costs of the system, which was because of the added treatment plant and pumping station costs. That, in turn, resulted in an increase in the average incremental cost of the system as well as the TACH.

iii) Scenario 3: Complete system with pumping station but excluding treatment plant costs

According to the result of this scenario, TACH of the sewerage system reduced from US$211 to US$31 at the population density of 100 persons/ha to 900 persons/ha respectively (See Figure 1 C). Interestingly, the simplified sewerage system became cheaper than UDDT at a population density of 196 persons/ha. This finding indicates that at the current population density in Chris Hanis of 281 persons/ha, simplified sewerage is still cheaper that onsite sanitation UDDT. The decrease in the population density at which the sewerage system became cheaper than the on-site sanitation UDDT compared to that in scenario (2) was due to the decrease in the total costs of the system, which was because of the excluded treatment plant construction costs. This, in turn, resulted in a decrease in the AIC of the system as well as TACH.

iv) Scenario 4: Complete system with treatment plant but excluding pumping station costs

From the results of this scenario (see Figure 1 D), it was noted that the TACH of the simplified sewerage system reduced from US$185 to US$28 at the population of 100 persons/ha to 900 persons/ha, respectively. The sewerage system became cheaper than on-site sanitation in this scenario at a population density of as low as 173 persons/ha. Therefore, based on the current population density within the studied area, which is 281 persons/ha, it is evident that simplified sewerage is still cheaper than on-site sanitation even in this scenario. The further decrease in the population density at which the sewerage system became cheaper than the on-site 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.

Implication of Results

The study revealed that the population density at which simplified sewerage system became cheaper than onsite sanitation UDDT in the Chris Hanis informal settlement area was between 118 to 216 persons/ha depending on the scenario under consideration. These results correlate well with the 160 persons/ha reported by Sinnatamby (1983) 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 118 and 216 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 on-site 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 economics 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.

CONCLUSIONS

This study examined the full costs of two '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 in Chris Hanis was US$113 and this was cost-efficient compared to sewerage in population densities less than 173persons/ha. However, it also varied between population densities less than 118 to 216persons/ha depending on the situation studied. It was confirmed that onsite sanitation (UDDT) was uneconomical for use in the informal settlement areas of Soweto where the population densities were more than 173persons/ha for which the onsite sanitation ceases to be economical.

2. The average TACH of simplified sewerage system in Soweto was US$ 55, and it varied between US$42 to US$71 depending on the local condition within the studied area. The system was cheaper than on-site sanitation at population densities greater than 173persons/ha (ranging from 118 to 216persons/ha.). 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$2.3 to US$4.7 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$3.0.

4. The population densities below 118 persons/ hectare, simplified sewerage is more expensive than on-site sanitation regardless of the modelled scenario. However, for population densities above 216persons/ hectare, in this case simplified sewerage became cheaper than on-site sanitations system, and this is really a very important finding. 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.

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SUPPLEMENTARY INFORMATION

Table S1: Total Costs considered while conducting economic analysis of studied sanitation technologies in Chris Hanis

Designed Scenarios	Total Costs (US$)				
	Capital costs	Maintenance Costs	Maintenance Costs (Discounted Cost)	Operation Costs	Operation Costs (Discounted Cost)
Scenario 1	109,294	404,697	151,326	699	205
Scenario 2	207,483	424,560	156,576	244,430	75,780
Scenario 3	149,928	424,560	156,576	244,430	75,780
Scenario 4	193,331	404,697	151,326	699	205
UDDT	590	801	248	607	222

Scenario 1: Simplified Sewerage System discharging in an existing conventional trunk sewer,
Scenario 2: Complete Simplified sewerage system with treatment plant and pumping station,
Scenario 3: Complete system with pumping station but excluding treatment plant costs,
Scenario 4: Complete system with treatment plant but excluding pumping station costs,
UDDT: Urine Diverting Dry Toilet.

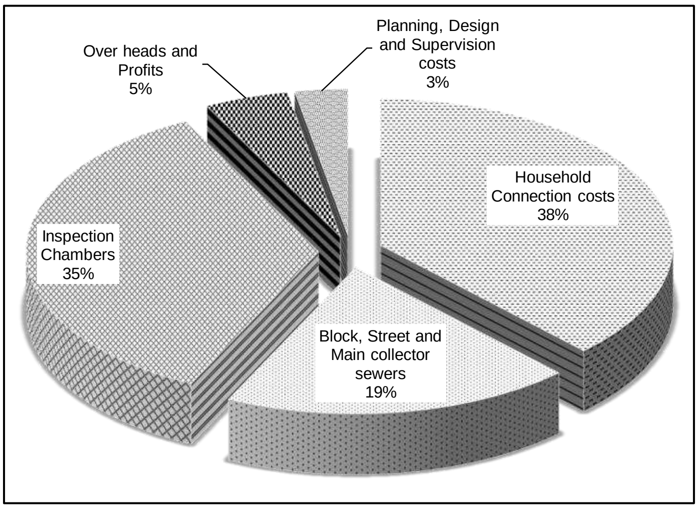

Figure S1: Elements considered for the Capital/ Construction costs of the simplified sewerage system discharging in an existing conventional trunk sewer (Scenario 1)

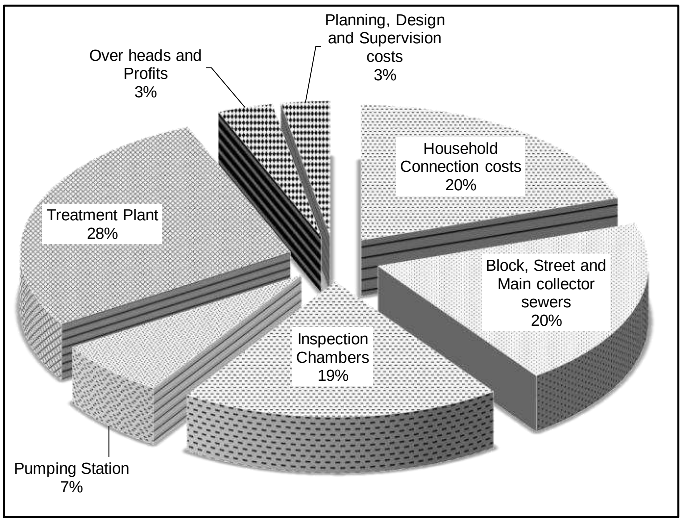

Figure S2: Elements considered for the Capital/ Construction costs of the complete simplified sewerage system with treatment plant and pumping station (Scenario 2)

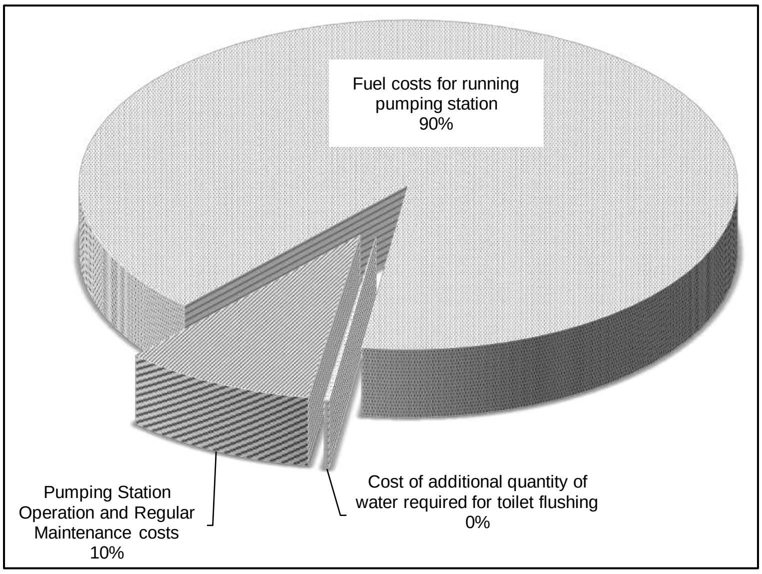

Figure S3: Elements considered for the operation costs of the complete simplified sewerage system with pumping station (Scenario 2)

Table S2: Cost elements considered during economic cost analysis of studied sanitation technologies in Chris Hanis

Designed Scenarios	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**UDDT**
Capital cost elements					
Household connection	√	√	√	√	-
Block, Street and Main collector sewers	√	√	√	√	-
Inspection Chambers	√	√	√	√	-
Pumping Station	-	√	√		-
Treatment Plant		√		√	-
Over heads and Profits	√	√	√	√	√
The Vault for UDDT	-	-	-	-	√
Soak pit					√
Planning, Design and Supervision costs	√	√	√	√	√
Operation and Maintenance Costs					
Fuel costs for running the pumping station	-	√	√	-	-
Pumping station replacement	-	√	√	-	-
Pumping station maintenance	-	√	√	-	-
Cost of additional quantity of water required for toilet flushing	√	√	√	√	-
Minor Repairs on the UDDT Vault	-	-	-	-	√
Labour costs	√	√	√	√	-
Sewer rodding machine hiring	√	√	√	√	-
Fuel cost for sewer rodding machine	√	√	√	√	-
Emptying and transport of faecal waste to the treatment facility	-	-	-	-	√

Scenario 1: Simplified Sewerage System discharging in an existing conventional trunk sewer,
Scenario 2: Complete Simplified sewerage system with treatment plant and pumping station,
Scenario 3: Complete system excluding treatment plant cost,
Scenario 4: Complete system excluding pumping station costs,
UDDT: Urine Diverting Dry Toilet.

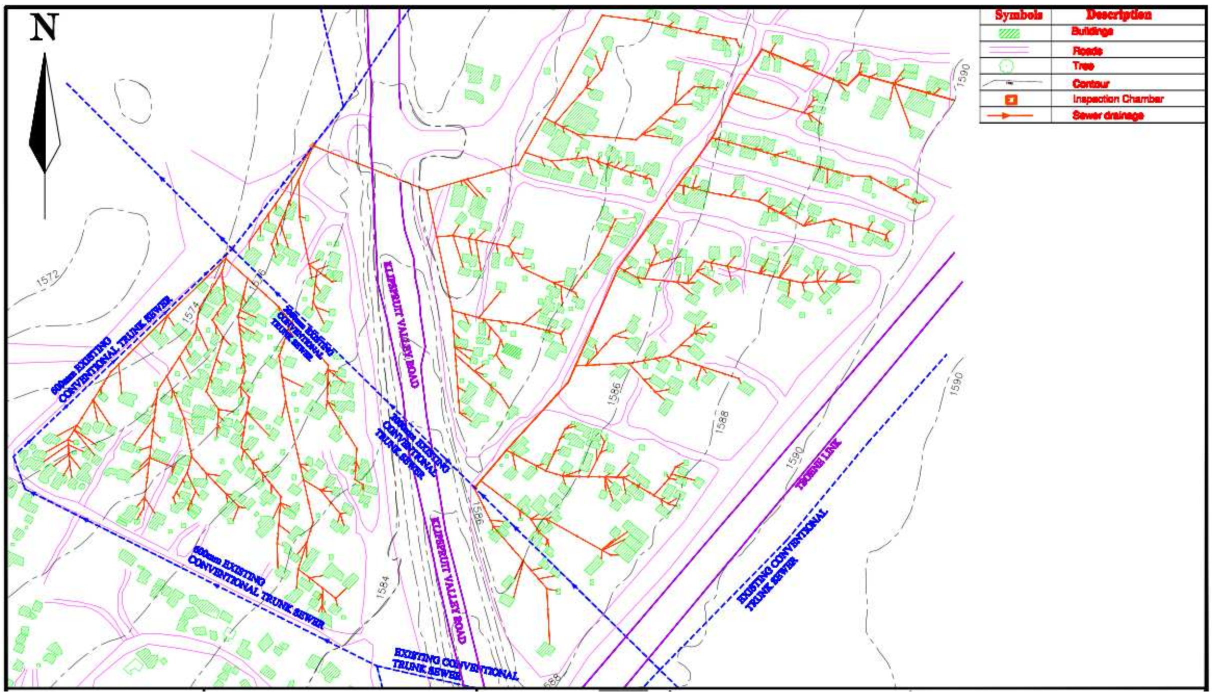

Figure S4: Modelled Simplified Sewerage layout in Chris Hanis, Soweto